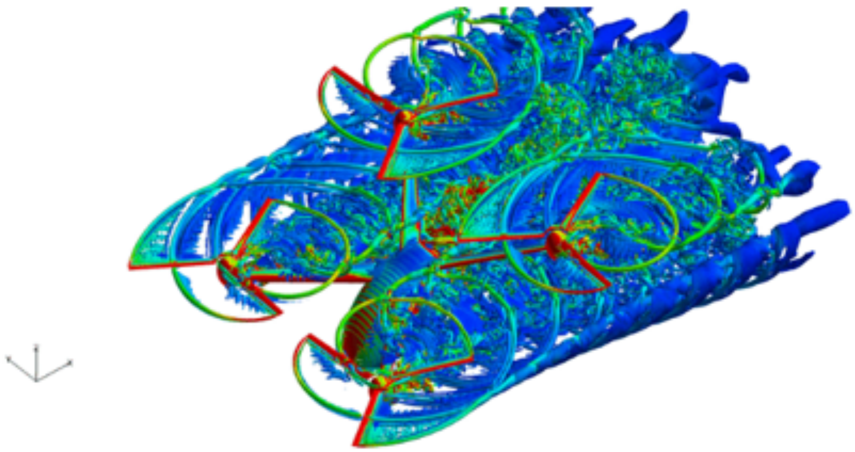
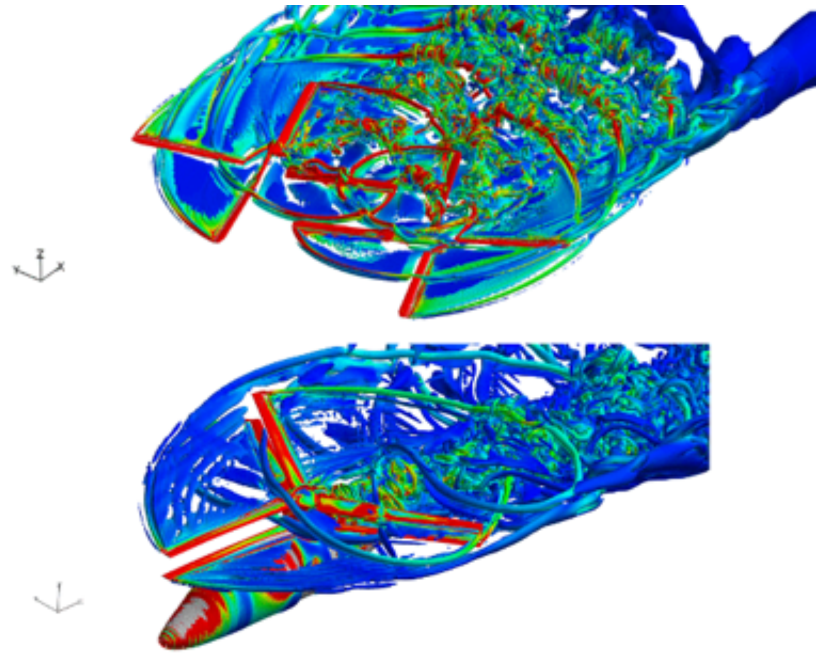
Aeroacoustic Predictions for a Lift-Offset Coaxial Rotor and





Zhongqi (Henry) Jia
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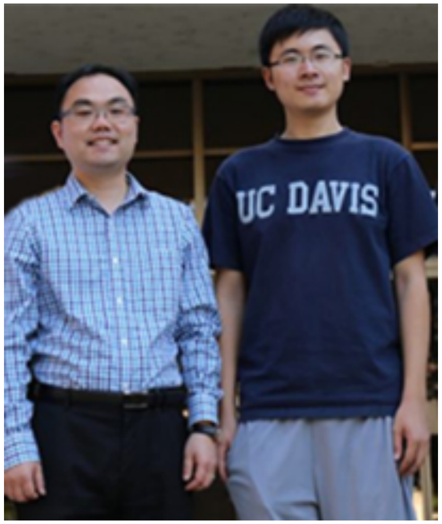
Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, December 10, 2020

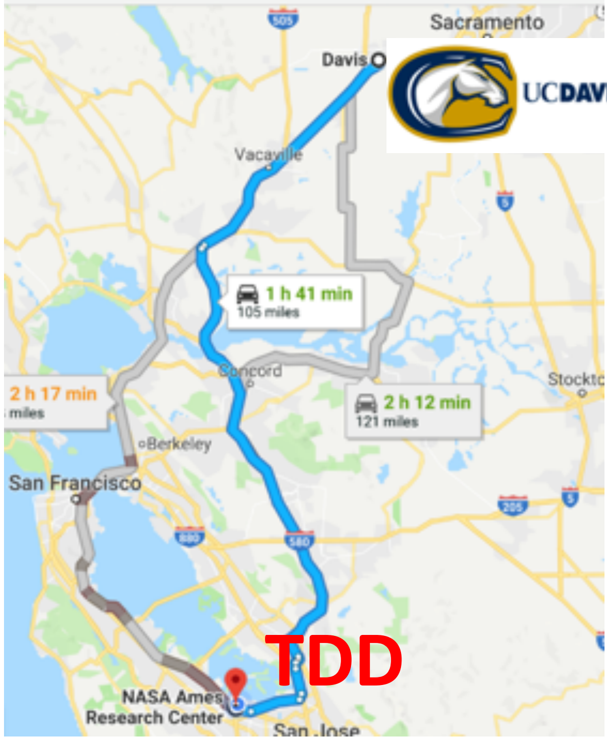
Outline

- Self Introduction
- Part 1: Lift Offset Coaxial Rotor
  - Introduction
  - Methods
  - Results
  - Summary
- Part 2: Urban Air Mobility Aircraft
  - Introduction
  - Methods
  - Results
  - Summary

Self Introduction



- 5th year Ph.D. candidate from UC Davis
  - Applied aerodynamics and aeroacoustics
  - Advised by Professor Seongkyu Lee
- Previous work/research experiences
  - 2016 NASA's MARTI (NASA Academy) program, NASA Ames
  - 2017 to 2020 summer internships at Army's Technology Development Directorate (TDD), Moffett Field
- Awards
  - 2019 Ph.D. and 2017 M.S. Vertical Flight Foundation scholarships
  - 2018 Joseph Steger Fellowship
  - 2017 N&M Sarigul-Klijn Flight Research Fellowship
  - 2016 MAE Department Fellowship



Self Introduction

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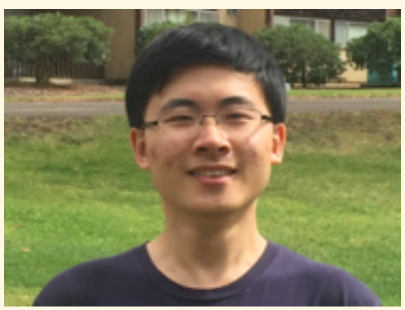
- **Vertical Lift Research Center of Excellence (VLRCOE) project collaboration with Penn State**
  - **Task: Fundamental Aeroacoustics of Lift-Offset Coaxial Helicopter Rotors**

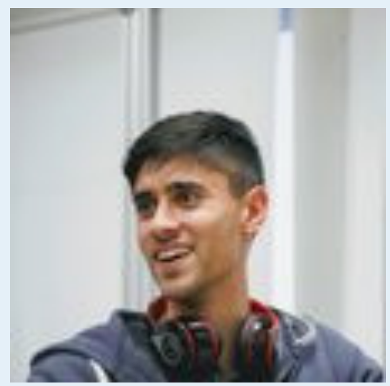
UC Davis



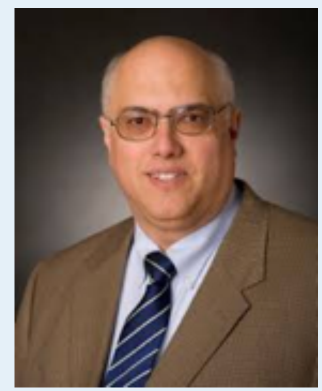
Ph.D. Candidate
Zhongqi (Henry) Jia

Professor
Seongkyu Lee

Penn State



Ph.D. Candidate
Kalki Sharma

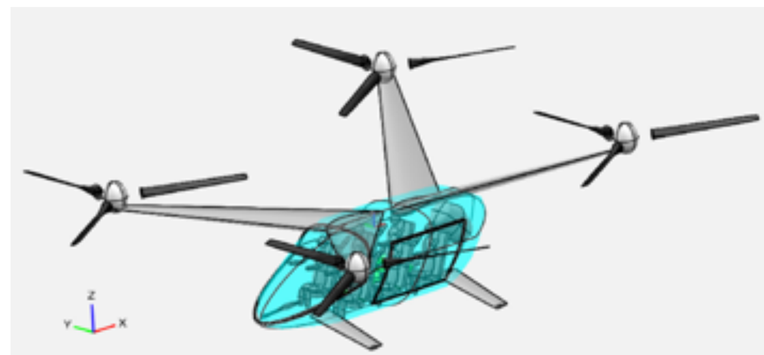


Professor
Kenneth S. Brentner

Self Introduction

- **Aerodynamics and aeroacoustics of multi-rotor Urban Air Mobility (UAM) vehicles**

NASA's One-Passenger Quadrotor



NASA's Six-Passenger Quadrotor

NASA's Six-Passenger Side-by-Side Rotor

Courtesy of Dr. Johnson and Chris Silva from Rotorcraft Aeromechanics, NASA Ames

Part 1: Lift Offset Coaxial Rotor

Introduction: Motivation

- A lift-offset coaxial rotor is considered for the next-generation rotorcraft
- Adopted the Advancing Blade Concept (ABC) from the Sikorsky XH-59A
- Potential noise issues due to mutual interactions between the upper and lower rotors
- Fundamental understanding of interactional aerodynamics and acoustics is critical

Sikorsky XH-59A

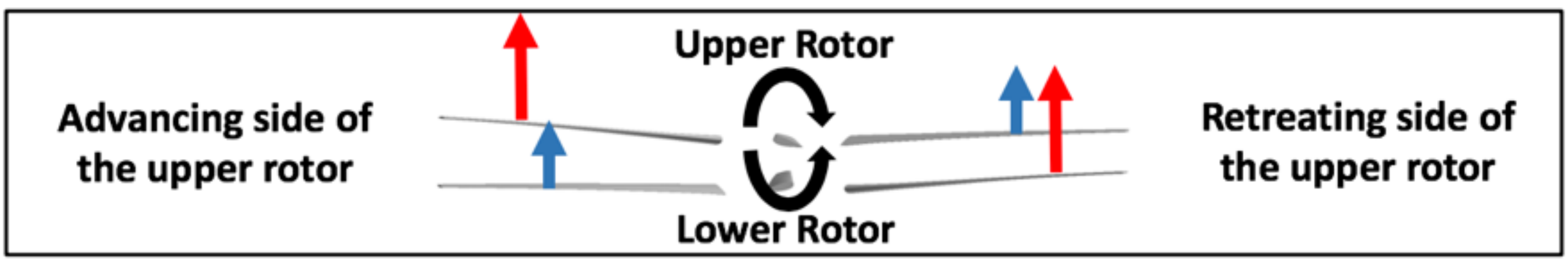
Sikorsky & Boeing SB>1 Defiant

Ref: Sikorsky photo gallery & archives

Introduction: Lift Offset

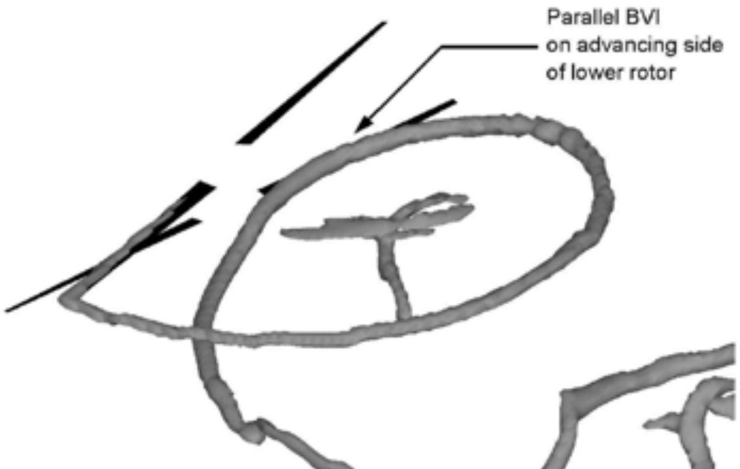
- Lift-offset (LO): the shift of integrated lift toward the advancing side of the rotor disk
- Each rotor carries a rolling moment of equal magnitude and opposite direction
- Mathematical expression:

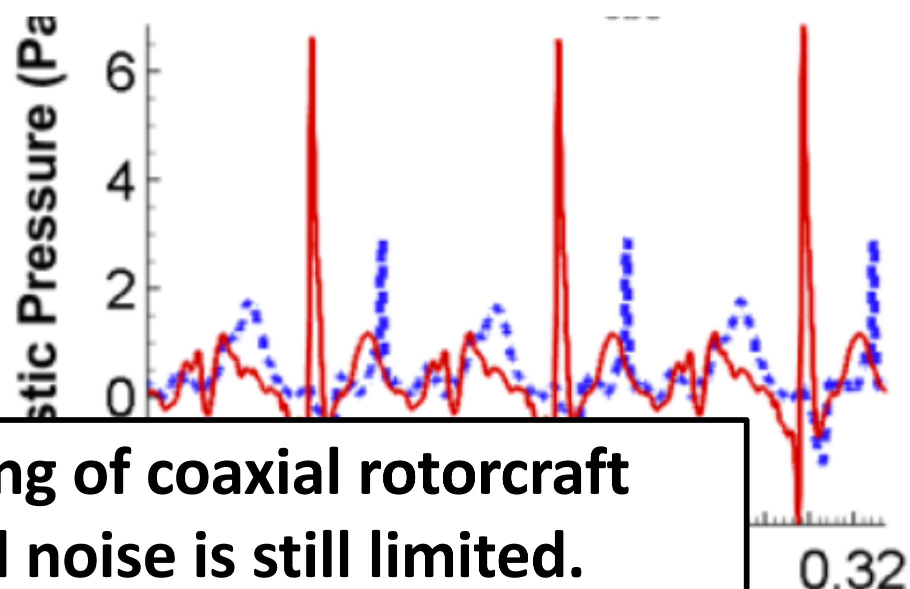
$$\mathrm{LO} = \frac{\Delta M_X}{T \cdot R}$$



Introduction: Literature Review

- **Parallel rotor-to-rotor blade vortex interaction (BVI) noise of a lift-offset rotor at low speed [Kim, H. W., et al., 64th AHS Annual Forum, 2008]**
- **BVI-like pressure pulses being identified for a lift-offset coaxial rotor [Walsh, G., et al., 72nd AHS Annual Forum, 2016]**





Fundamental understanding of coaxial rotorcraft aerodynamically induced noise is still limited.

Ref: Kim, H. W., et al., 64th AHS Annual Forum, 2008

Ref: Walsh, G., et al., 72nd AHS Annual Forum, 2016

Introduction: Research Objectives

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- Predict the acoustics of a **lift-offset** coaxial rotor in **high-speed** forward flight based a high-fidelity **CFD/CSD loose coupling** approach
- Identify the **noise sources** of a lift-offset coaxial rotor
- Perform **parametric studies**: flight speed, lift-offset value, rotor-to-rotor separation distance, and vehicle pitch attitude
- Correlate rotor acoustics with **vehicle performance** for the lift-offset coaxial rotor
- Investigate the **interactional acoustics** of a **full-configuration** coaxial model

Methods: Aircraft Model

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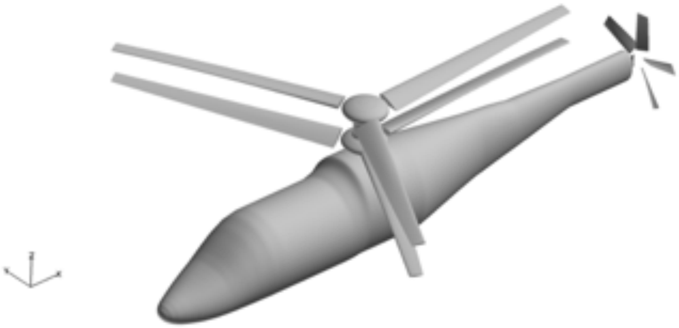
- **Aircrat model: the Sikorsky XH-59A**

Main Rotor Properties	Descriptions
Blades Per Rotor	3
Rotor Radius (ft)	18 ft (5.5 m)
Nominal Rotor Speed	345 RPM
Nominal Tip Speed	650 ft/sec (198 m/s)

Sikorsky XH-59A

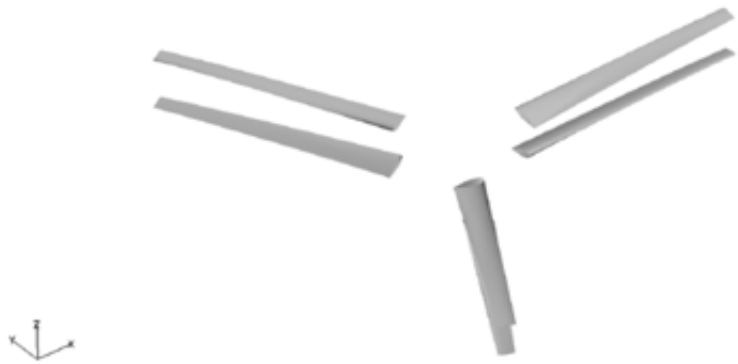
Propeller Properties	Descriptions
Number of Blades	5
Rotor Radius (ft)	3.6 ft (1.1 m)
Nominal Rotor Speed	2068.4 RPM
Nominal Tip Speed	775 ft/sec (236.1 m/s)



Full Configuration CFD Model

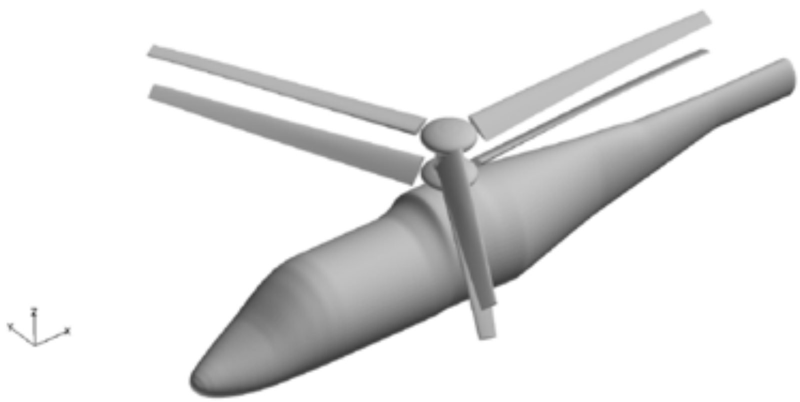
Methods: Aircraft Model

- **The four CFD models:**

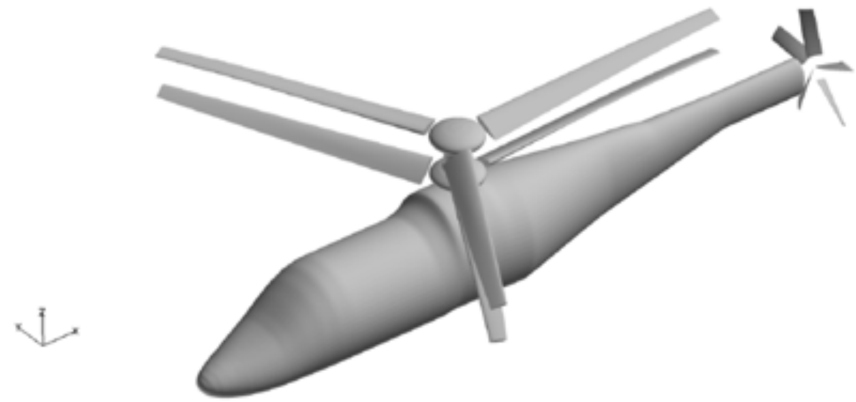


Isolated coaxial rotor (without the hub)

Isolated coaxial rotor (with the hub)



Fuselage case

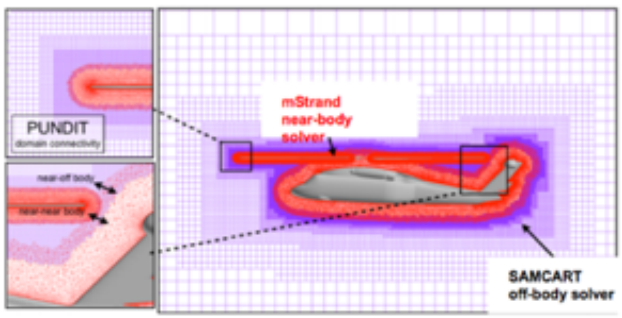


Full configuration case

Methods: CFD Software

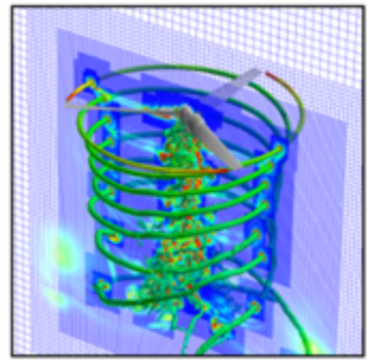
- **Software: HPCMP CREATE™-AV Helios**

Dual Mesh Paradigm



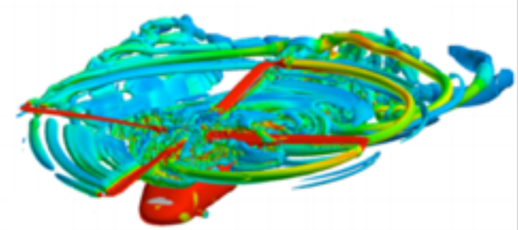
Near-body – mStrand, Overflow, FUN3D, …
Cartesian off-body - SAMCart

Adaptive Mesh Refinement



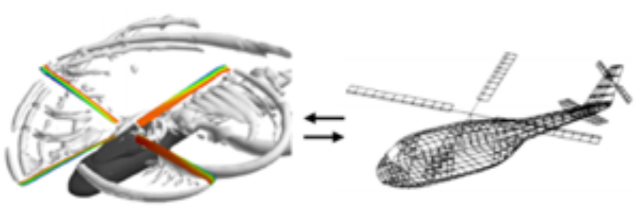
To resolve wake

Moving Body Overset



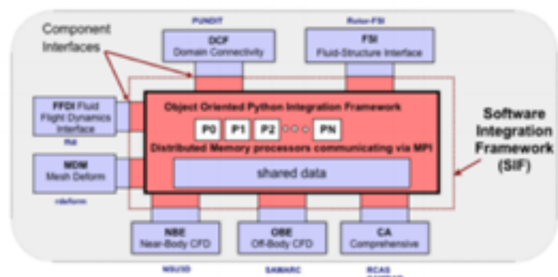
Rotor-Fuselage and Multi-rotor moving mesh support

CFD/CSD Coupling



RCAS and CAMRAD Structural Dynamics and Trim coupling

Advanced Software Infrastructure



Python-based infrastructure readily supports addition of new software

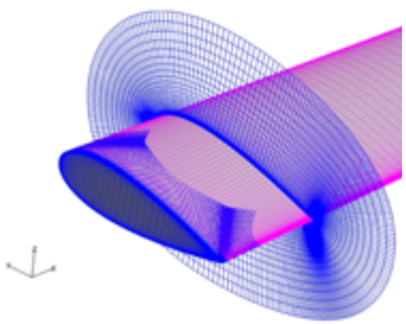
High Performance Computing

Runs on HPC hardware with focus on parallel scalability

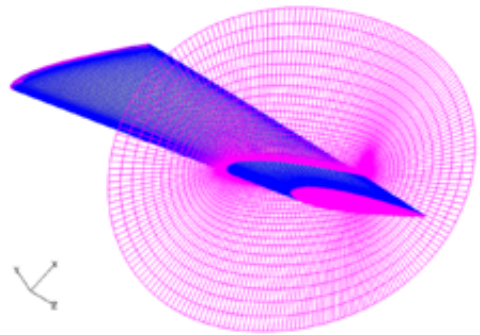
Sitaraman et al., "Progress in Strand/Cartesian Overset CFD Simulations Using CREATE™ –AV Helios", NASA Ames Seminar, May 25, 2017

Methods: CFD Mesh

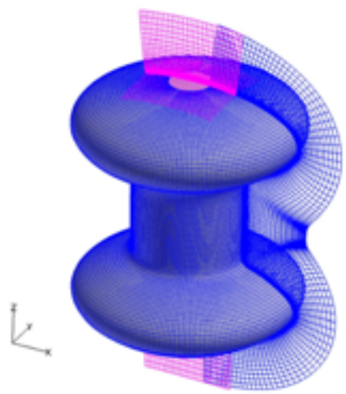
Near-Body Grids (Chimera Grid Tools)



Rotor blade
5M grids/blade

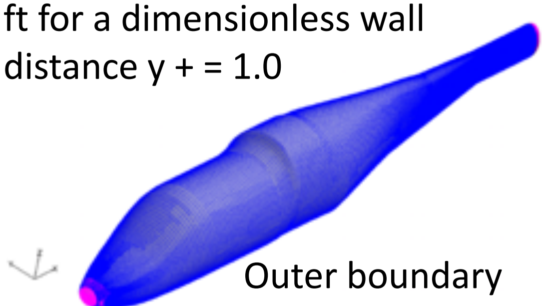


Propeller blade
1.9M grid pts/blade



Rotor hub (1.8M)

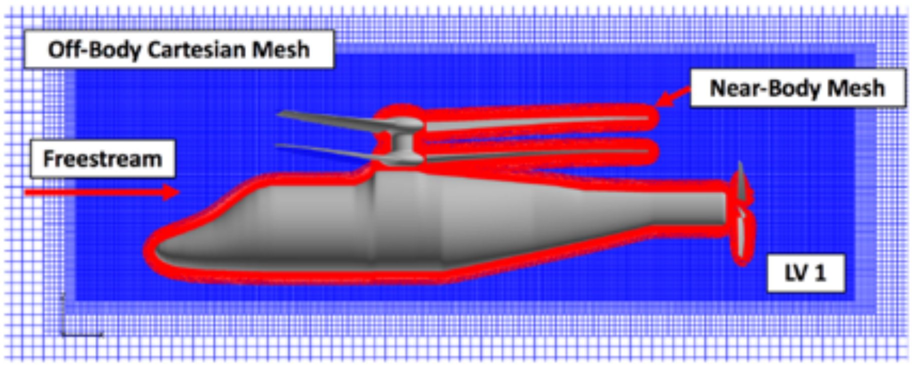
Initial wall spacing: 5×10^{-6} ft for a dimensionless wall distance $y+ = 1.0$



Outer boundary spacing: 10% C_{tip}

Fuselage (3.8M)

Off-Body Grids (SAMCart)



- Far-field dimension: 20 rotor radii
- 8 levels of Adaptive Mesh Refinement w/ Level-1 spacing = 10% C_{tip}
- Total: 102 M grid pts (1st time step)

Methods: CFD Setup

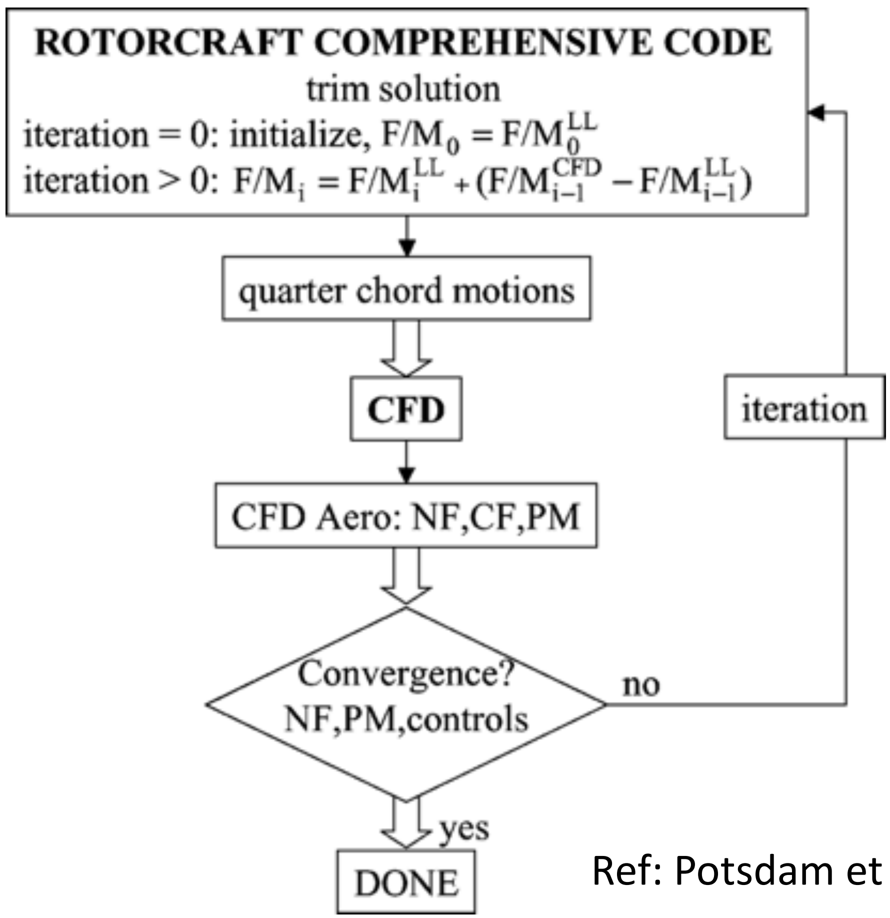
- **Summary (Helios Simulations):**

Input Parameters	Near-Body Grid	Off-Body Grid
CFD solver	OVERFLOW	SAMCART
Spatial scheme	5th order	5th order
Temporal scheme	2nd order	2nd order
Time step size	0.25°	
Turbulence Model	SA-DES	
Frequency of blade surface output	0.50° (every two time steps)	

- **CFD/CSD loose coupling at every half rotor rev/180° after the first rotor rev**
- **Full configuration case: every rotor rev/360°**

Methods: CFD/CSD Setup

- **CFD/CSD loose coupling between OVERFLOW and RCAS**
- **The CFD/CSD flow chart:**



Ref: Potsdam et al., Journal of Aircraft, 2006

Methods: Acoustics Prediction

- **PSU-WOPWOP**
  - **Numerically solves Farassat's Formulation 1A of the Ffowcs Williams and Hawkings (FW-H) equation**
  - **Impermeable surface strategy is used (the quadrupole source term is neglected)**

$$p'(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t)$$

$$4\pi p'_T(\vec{x},t) = \int_{f=0}\left[\frac{\rho_o(\dot{v}_n + v_{\dot{n}})}{r|1-M_r|^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_o v_n(r\dot{M}_r + c(M_r - M^2))}{r^2|1-M_r|^3}\right]_{ret} dS$$

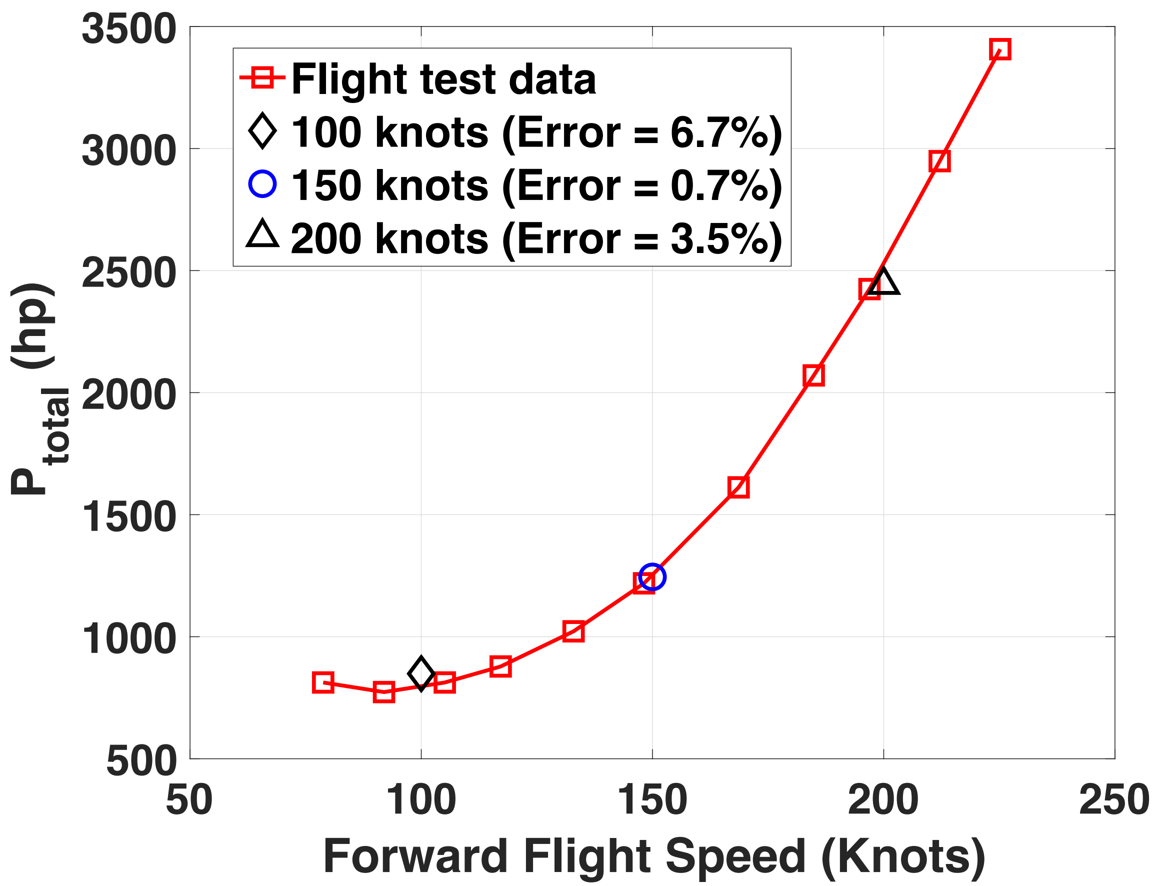
1. The Doppler amplification factor $1/(1-M_r)$ in each term

$$4\pi p'_L(\vec{x},t) = \frac{1}{c}\int_{f=0}\left[\frac{\dot{l}_r}{r|1-M_r|^2}\right]_{ret} dS + \int_{f=0}\left[\frac{l_r - l_M}{r^2|1-M_r|^2}\right]_{ret} dS + \frac{1}{c}\int_{f=0}\left[\frac{l_r(r\dot{M}_r + c(M_r - M^2))}{r^2|1-M_r|^3}\right]_{ret} dS$$

2. Change of blade surface loading with respect to change of acoustic source emission time or retarded time $\dot{l}_r$

Results: Power validation

- Simulated at 100, 150, 200 knots in forward flight (3,000 ft altitude) with zero vehicle pitch attitude
- Vehicle power validation (assuming LO = 0.2)



Results: Lift-Offset Coaxial Rotor

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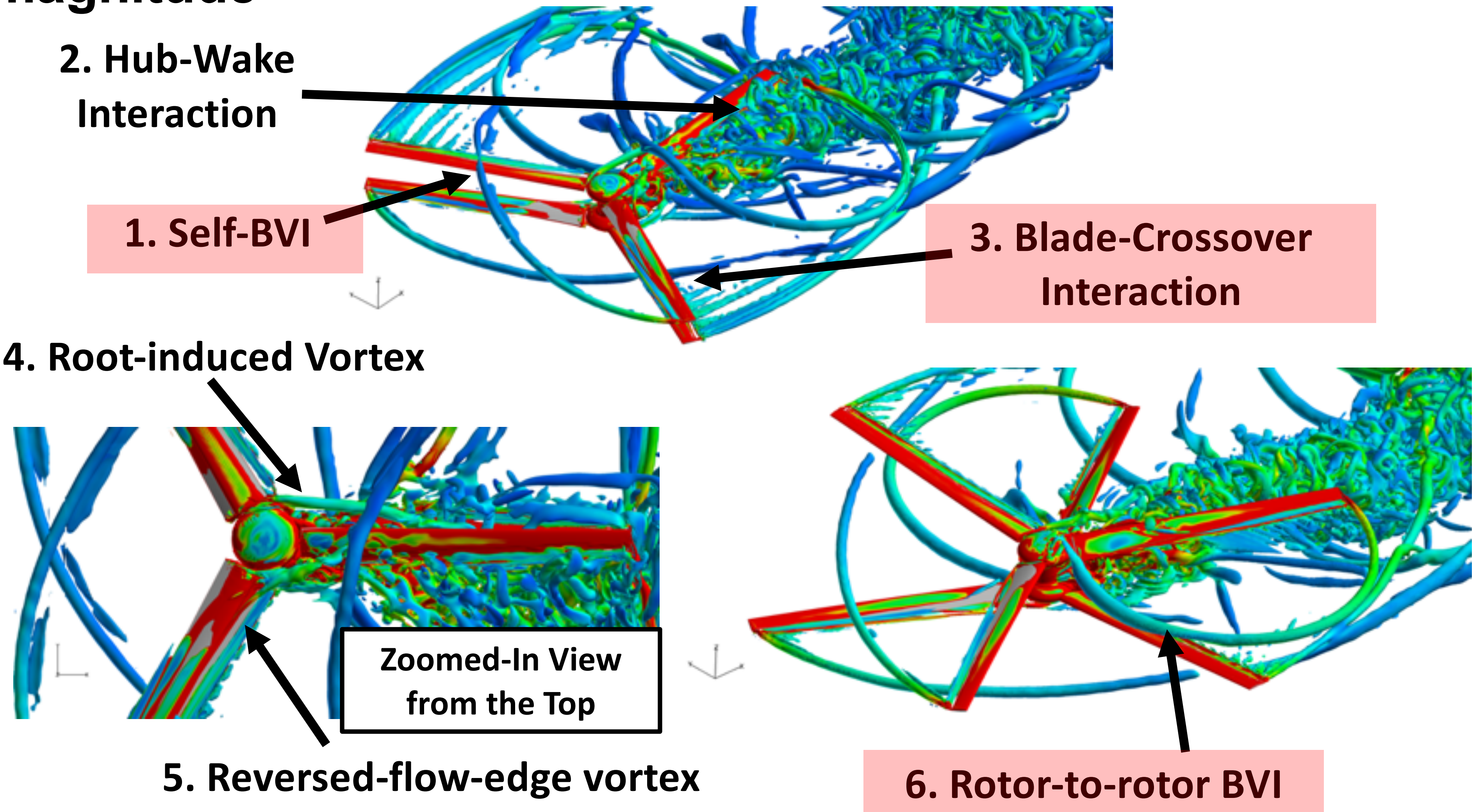
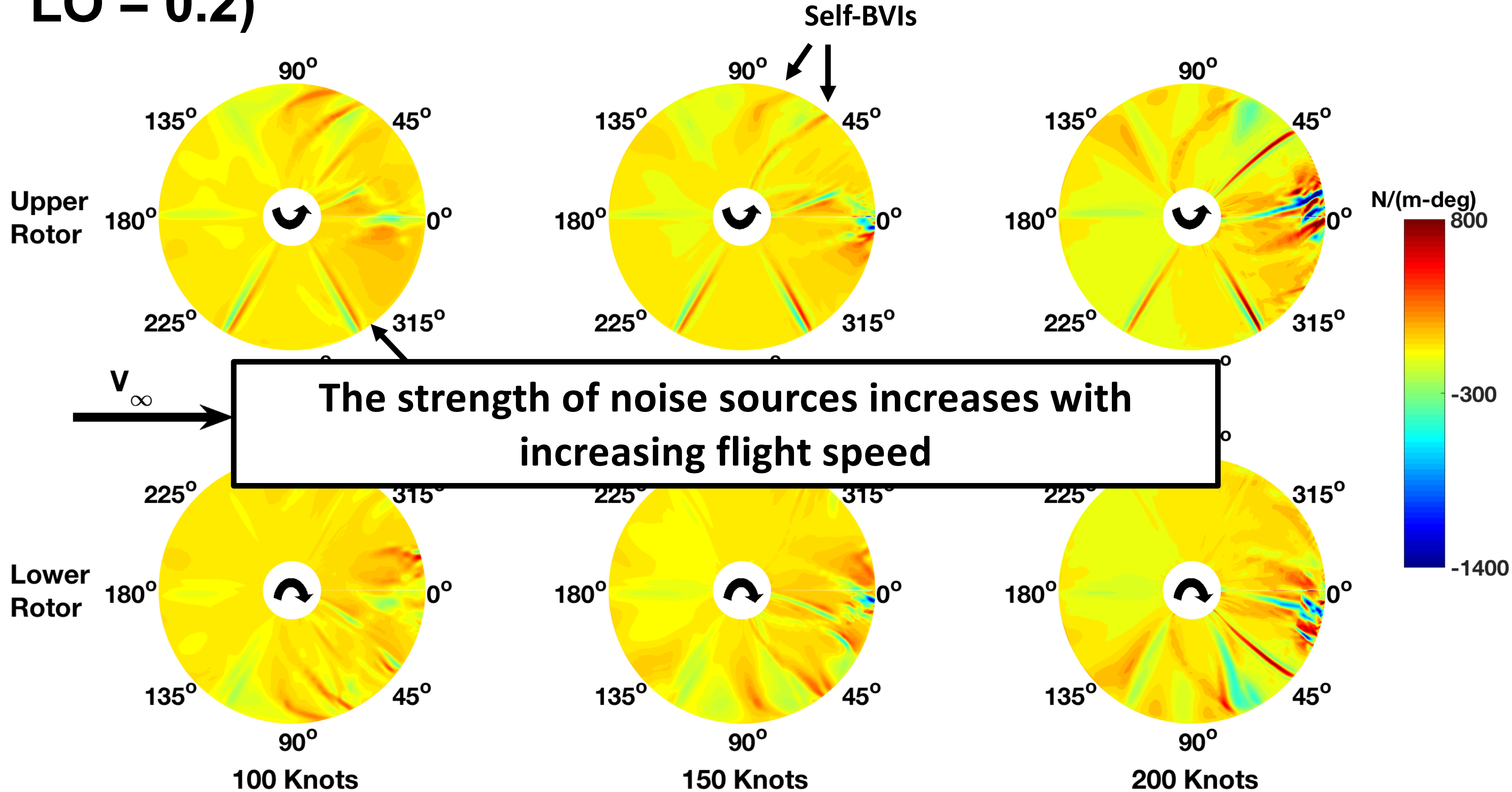
- Aerodynamic interactions at 150 knots (LO = 0.2)
- Iso-surface of q-criterion colored by vorticity magnitude



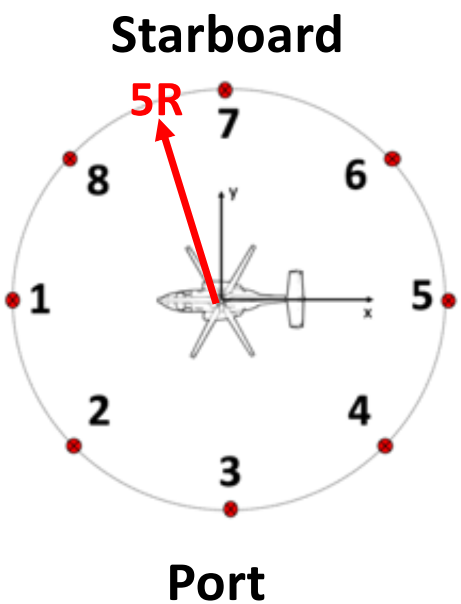
Results: Lift-Offset Coaxial Rotor

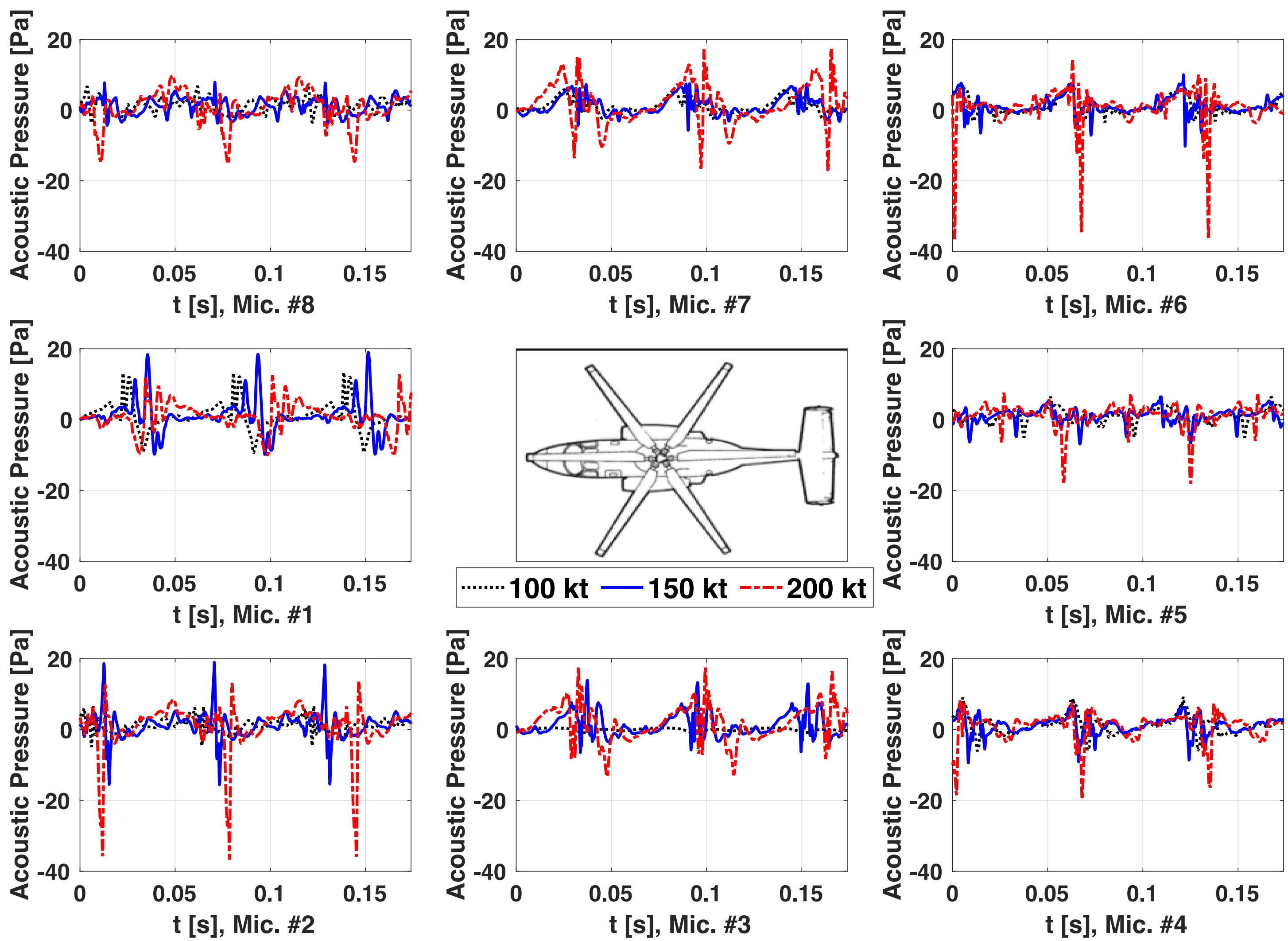
- **Azimuthal derivative of sectional normal force ($\dot{l}_r$) for the three speed cases (zero vehicle pitch attitude & LO = 0.2)**



Results: Lift-Offset Coaxial Rotor

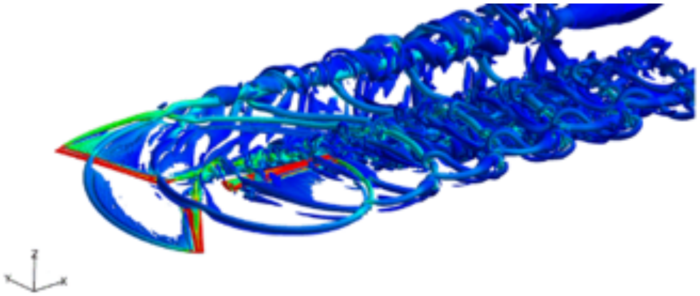
Loading Noise Acoustic Pressure (p'_L)



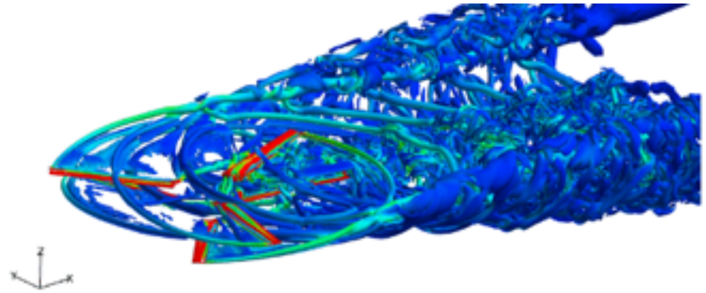


Results: Lift-Offset Coaxial Rotor

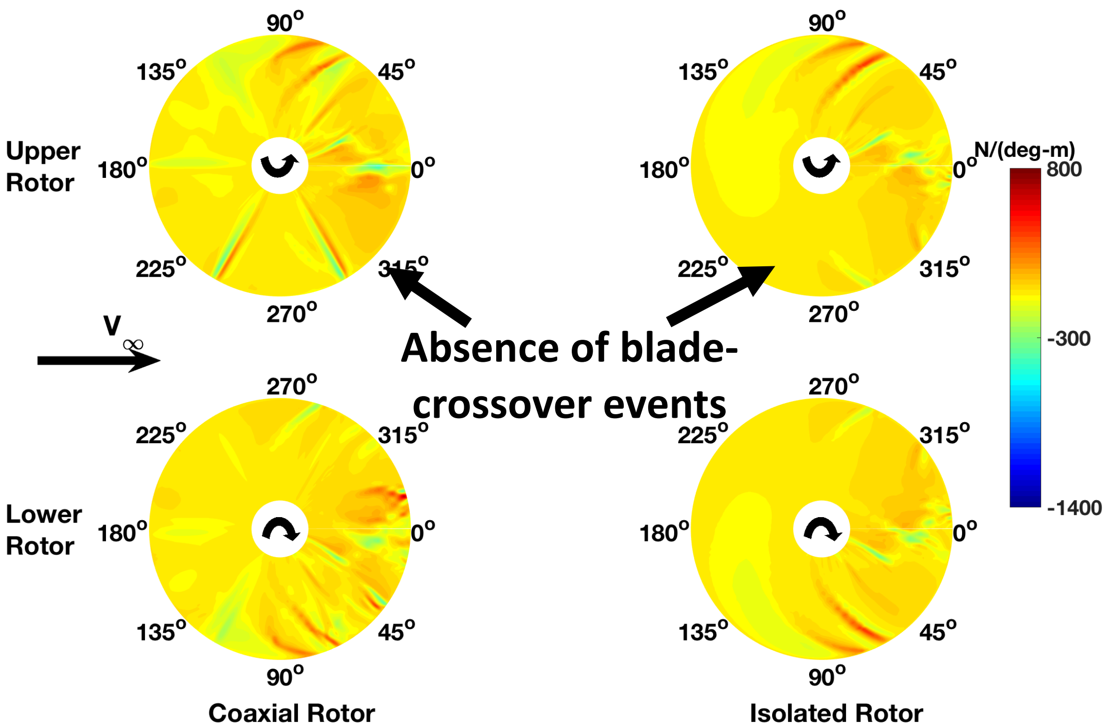
- **Single rotor (isolated upper rotor) vs. upper of the coaxial rotor at 100 knots**

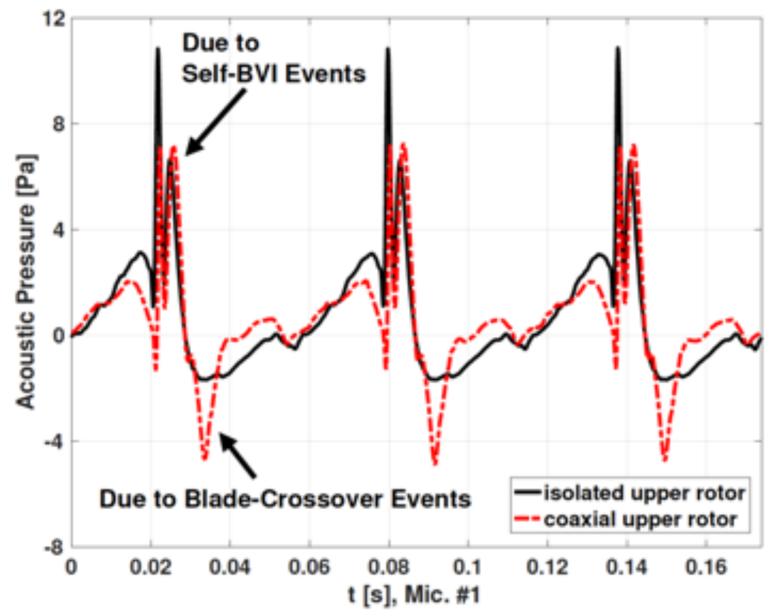


Single Rotor



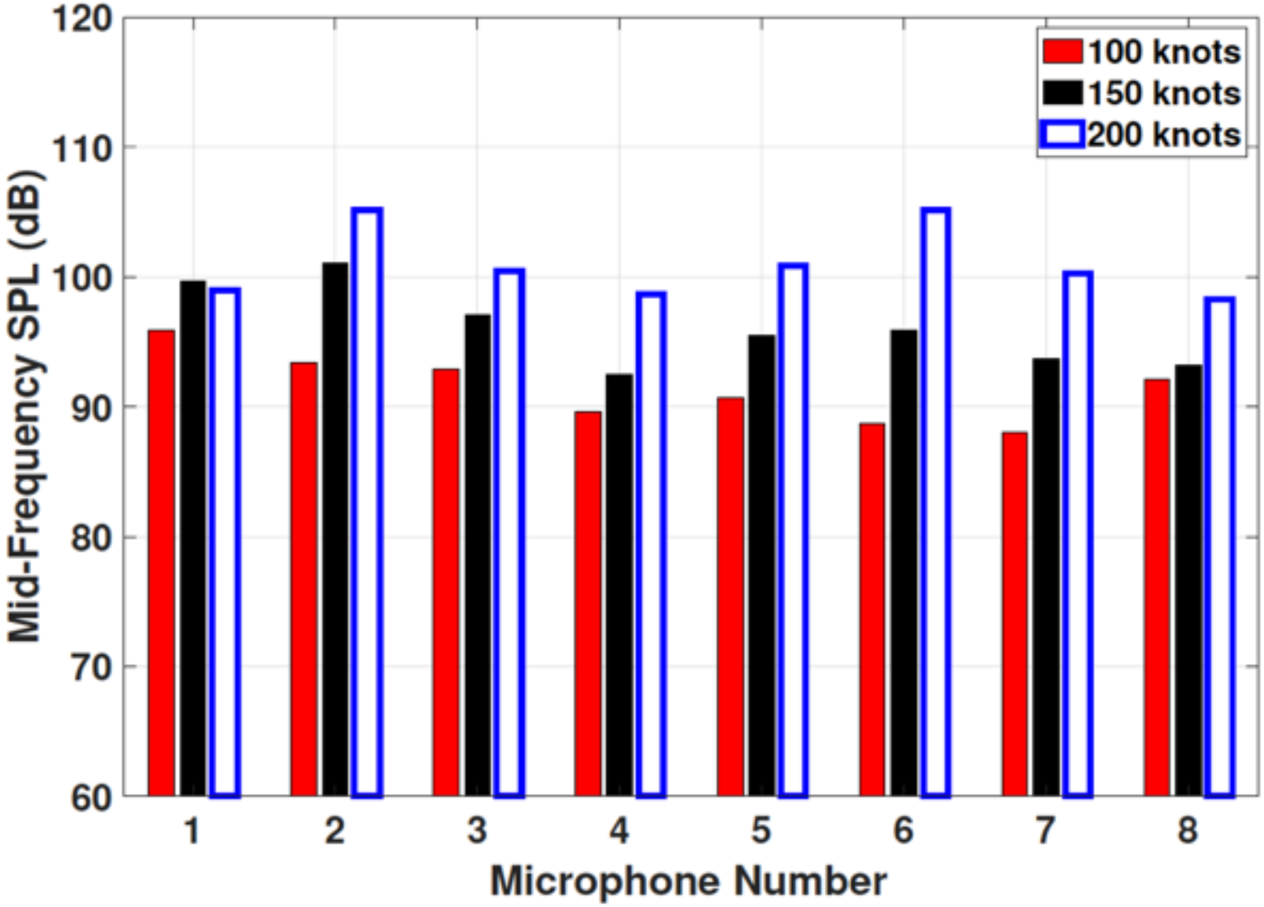
Coaxial Rotor

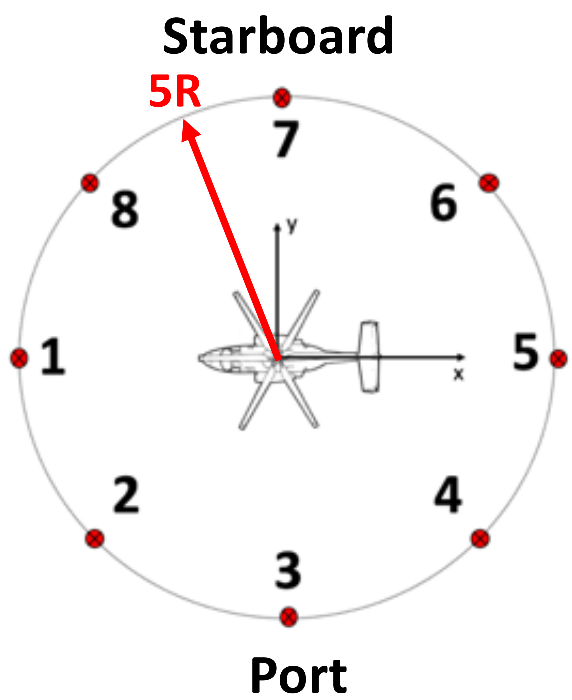




Results: Lift-Offset Coaxial Rotor

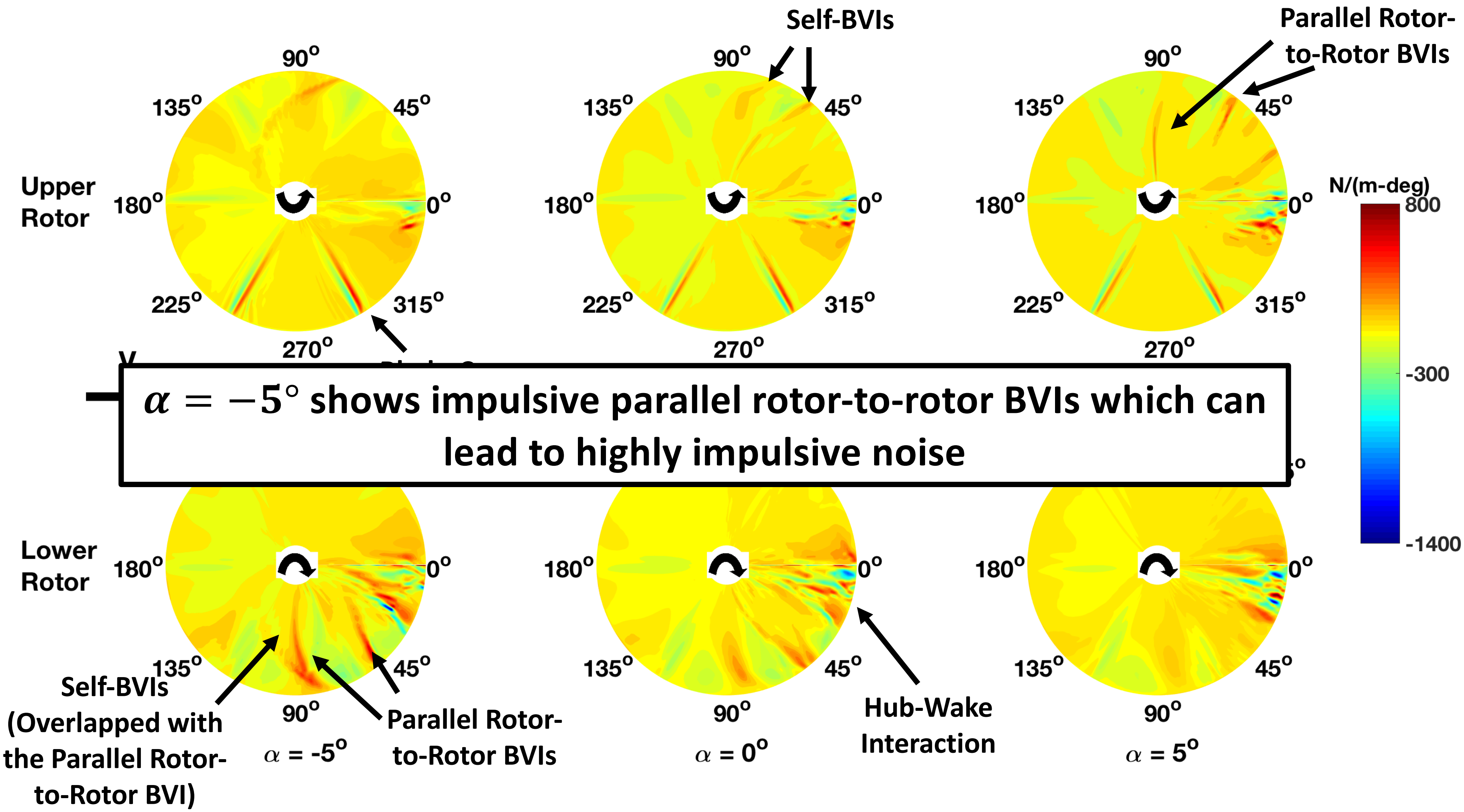
- **Effect of flight speed**
- **Comparison of mid-frequency SPL**





Results: Lift-Offset Coaxial Rotor

- **Azimuthal derivative of sectional normal force ($\dot{l}_r$) at 150 knots (three vehicle pitch attitude (α) cases)**



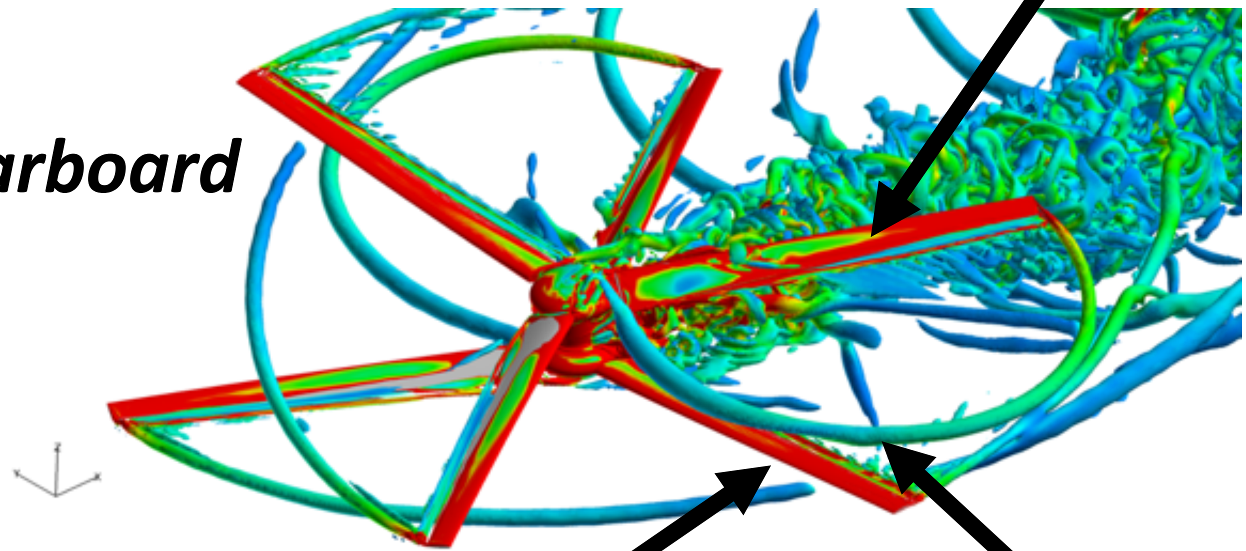
$\alpha = -5^\circ$ shows impulsive parallel rotor-to-rotor BVIs which can lead to highly impulsive noise

Results: Lift-Offset Coaxial Rotor

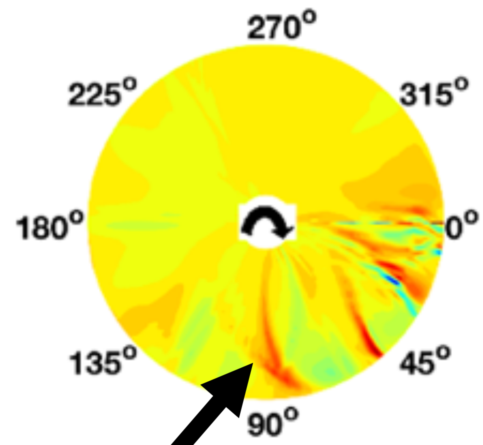
- **Parallel rotor-to-rotor BVI at $\alpha = -5^o$ (150 knots)**

Upper Rotor Blade

Starboard



Lower Rotor

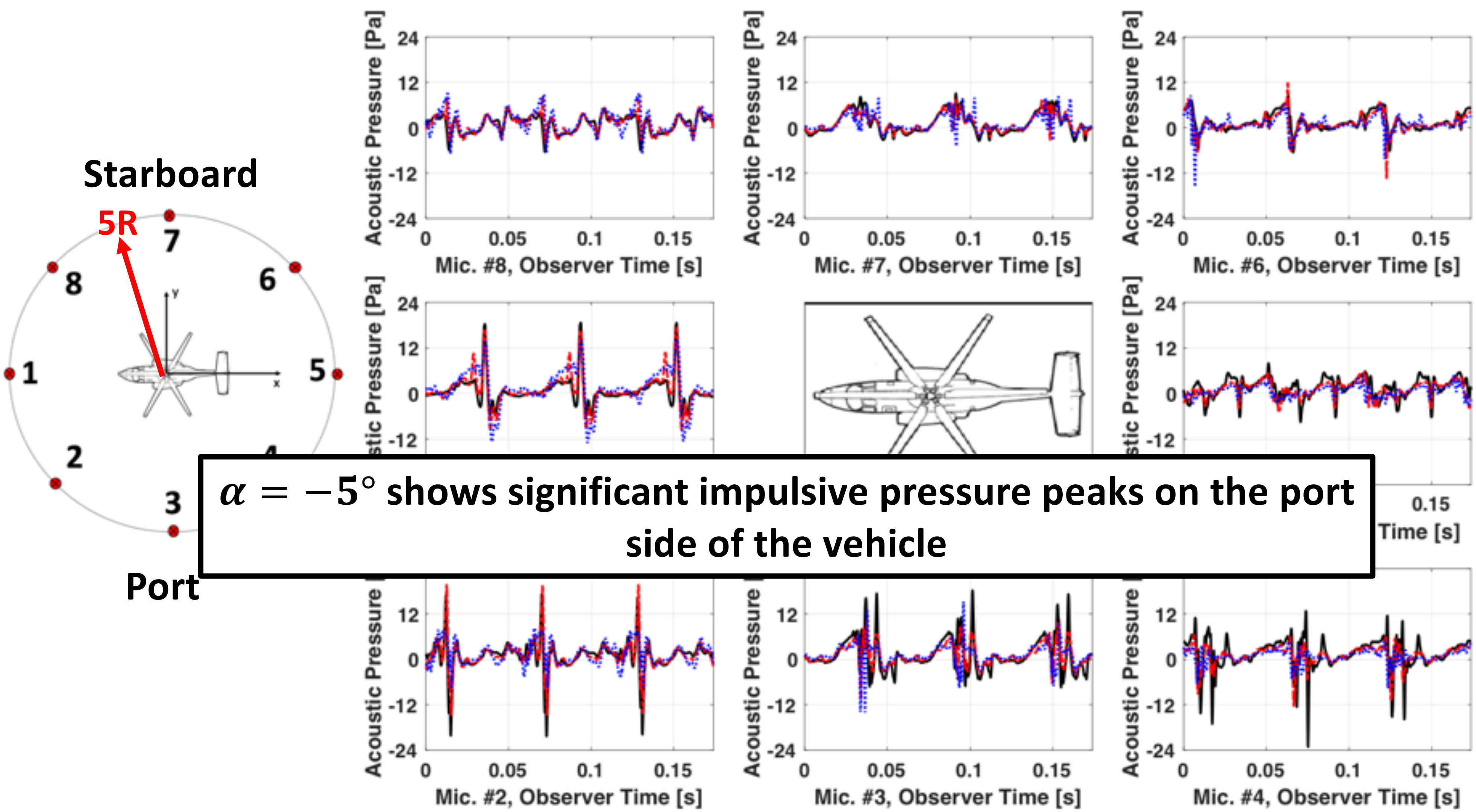


Lower Rotor Blade

Rotor-to-Rotor BVI (Parallel & Above the Surface)

Results: Lift-Offset Coaxial Rotor

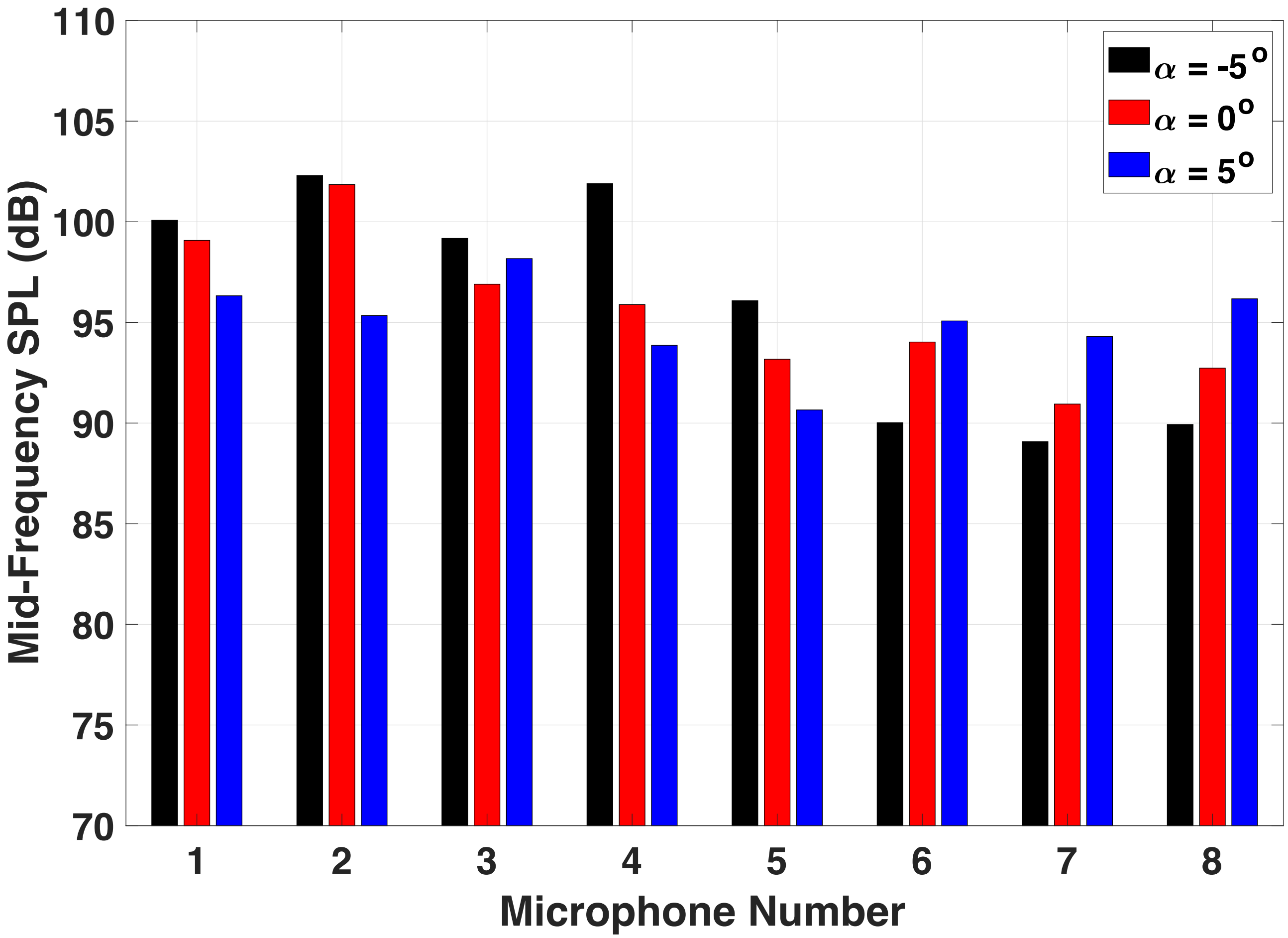
Loading Noise Acoustic Pressure (p'_L) at 150 knots

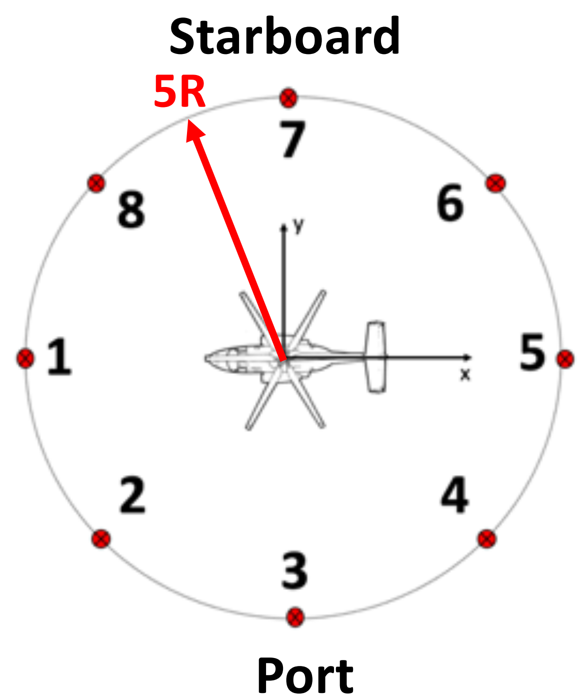


$\alpha = -5°$ shows significant impulsive pressure peaks on the port side of the vehicle

Results: Lift-Offset Coaxial Rotor

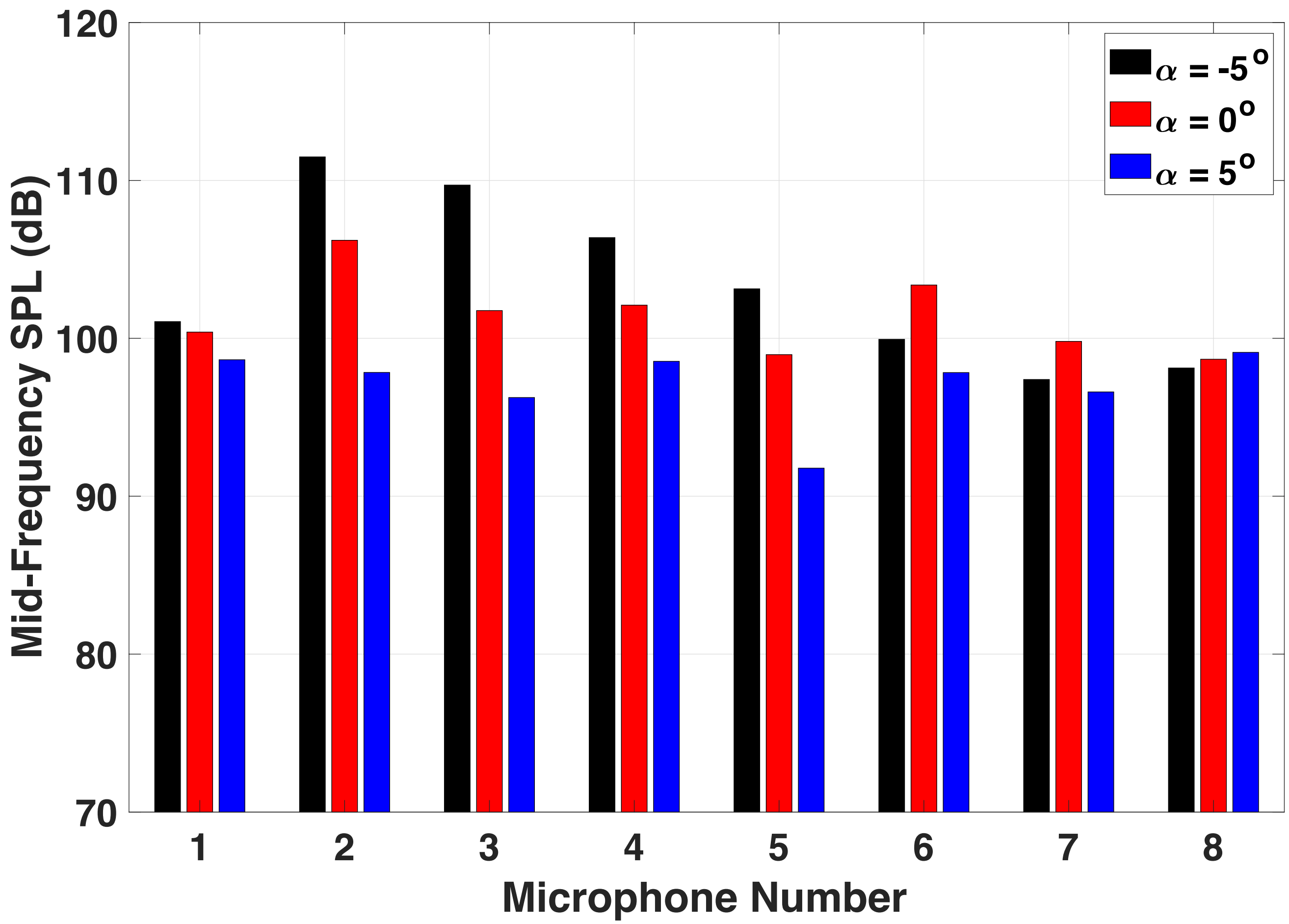
- **A comparison of mid-frequency sound pressure level at 150 knots**
  - **Computed between the 10th and 50th blade harmonics**

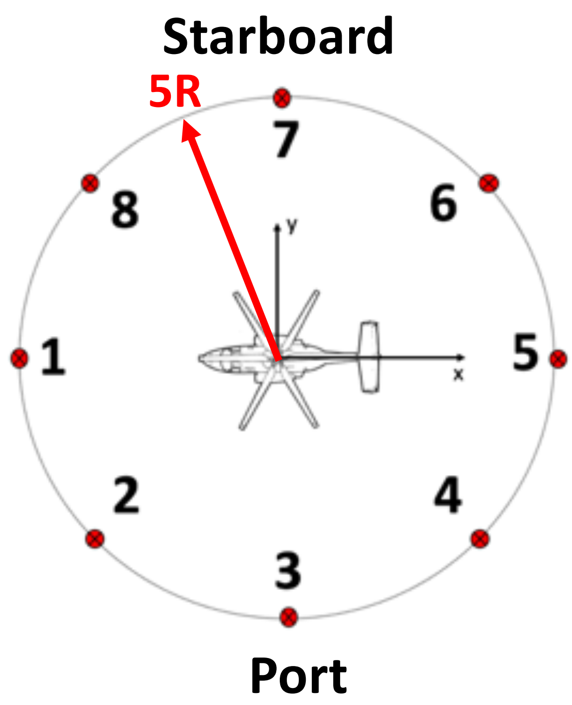




Results: Lift-Offset Coaxial Rotor

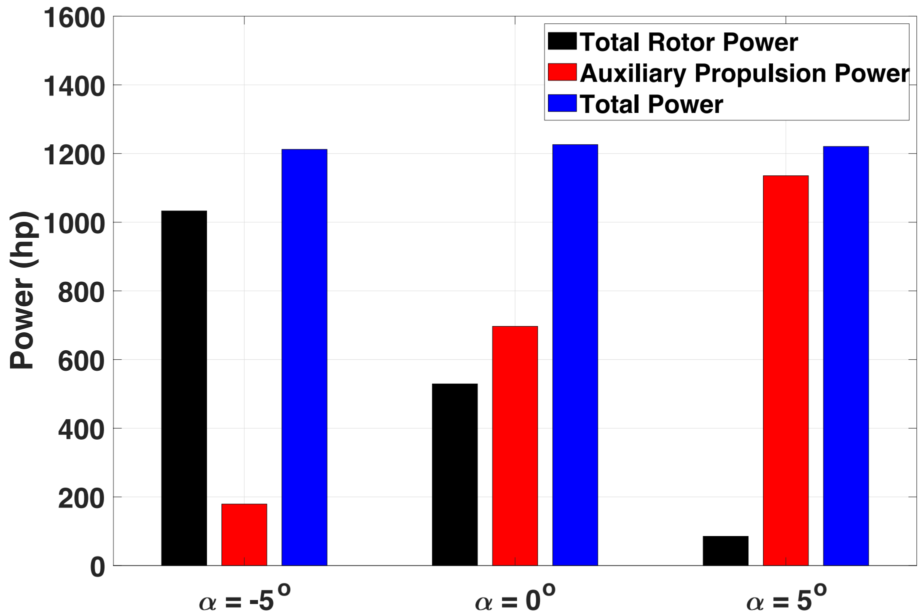
- **A comparison of mid-frequency sound pressure level at 200 knots**
  - **Computed between the 10th and 50th blade harmonics**



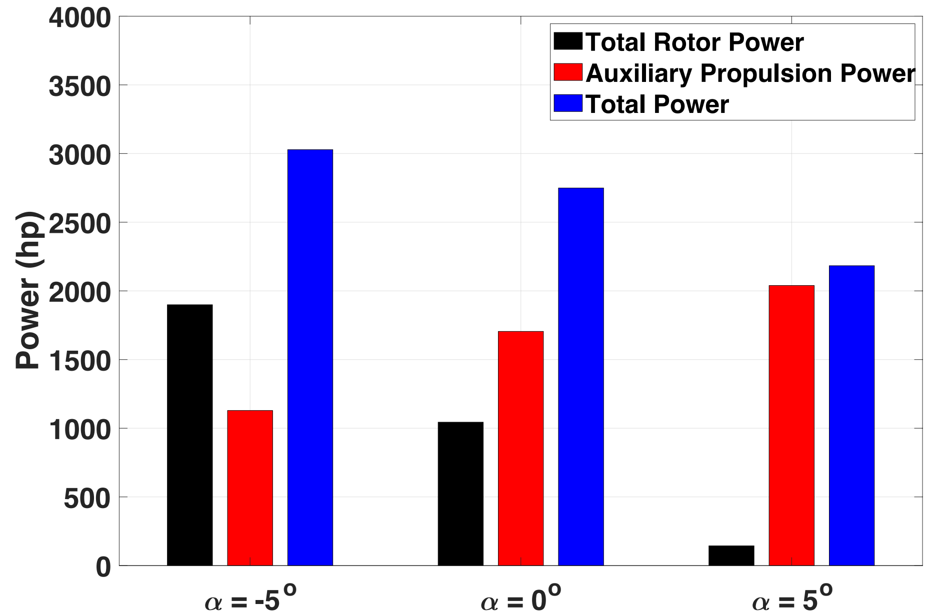


Results: Lift-Offset Coaxial Rotor

- **Power Performance**
  - At high speed, $\alpha = 5^o$ shows better power and acoustic performance
  - $\alpha = 5^o$ shows the lowest mid-frequency SPL at 200 knots



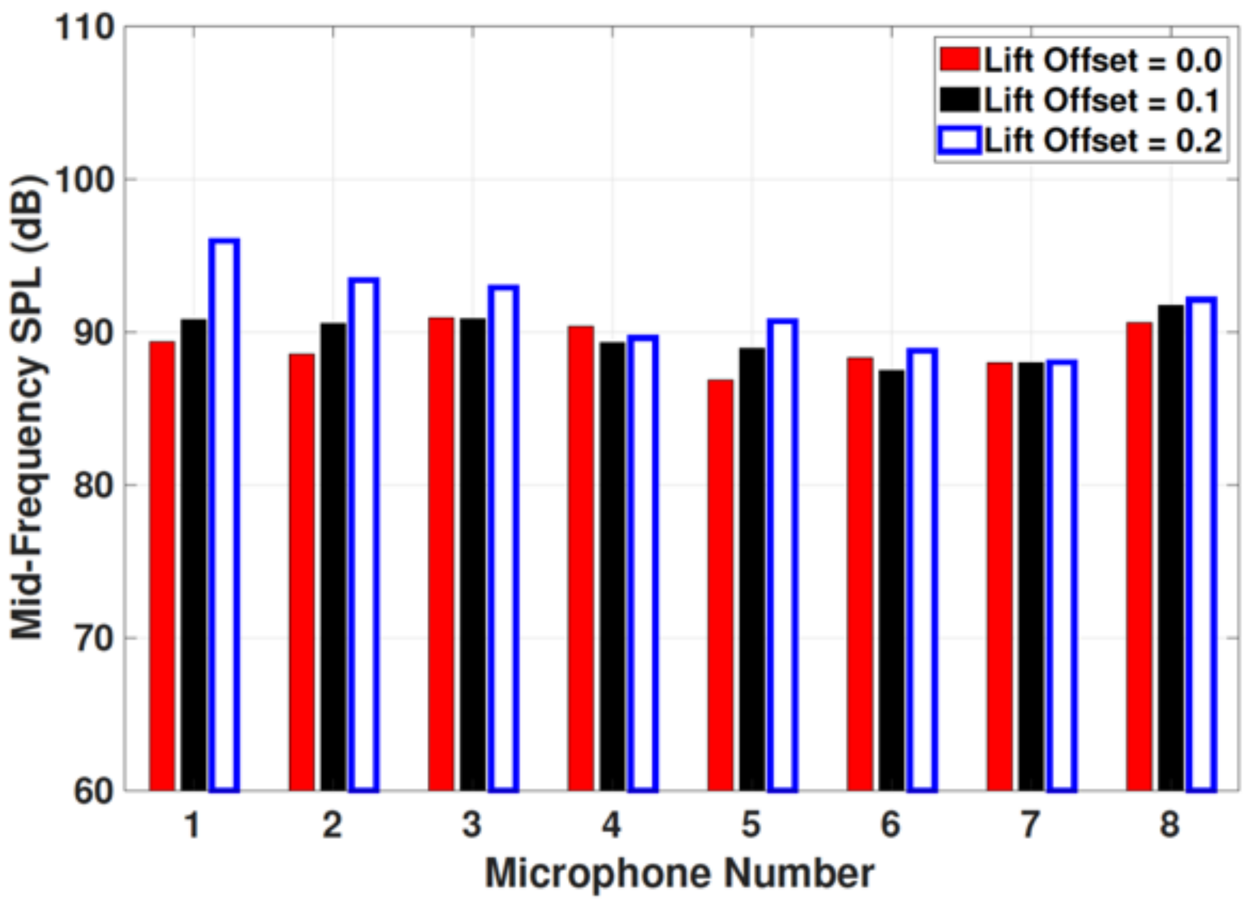
150 Knots

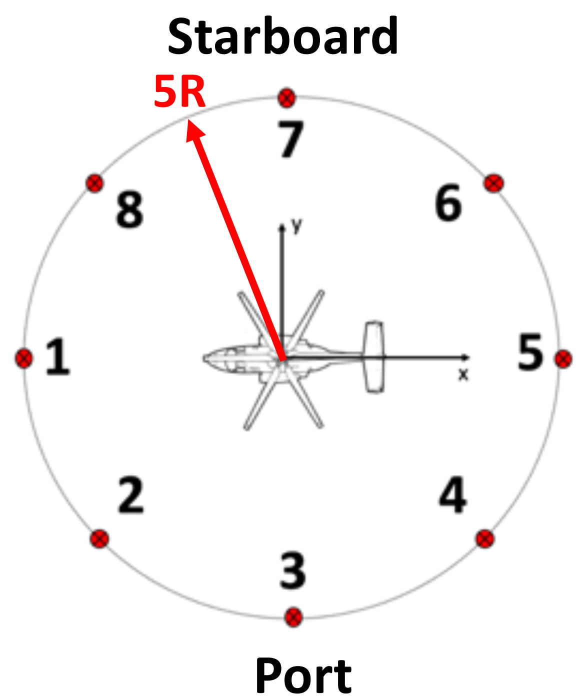


200 Knots

Results: Lift-Offset Coaxial Rotor

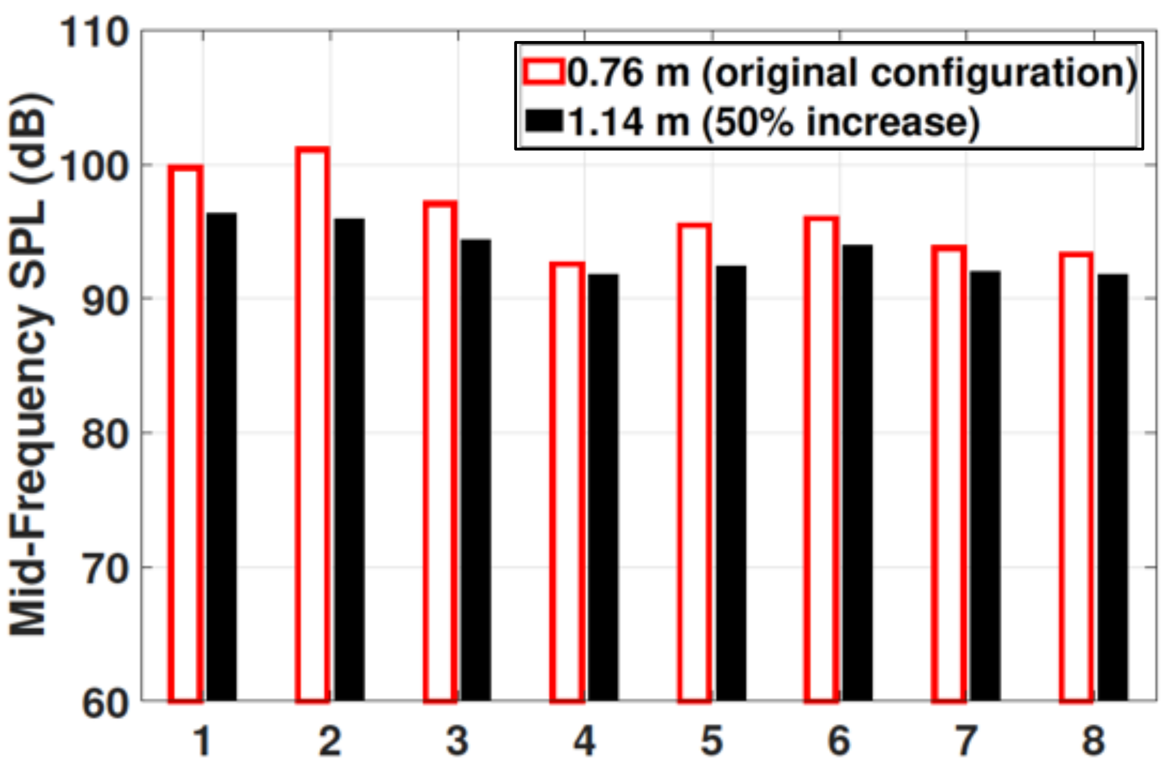
- Effect of the lift offset value (LO) at 100 knots
- Comparison of mid-frequency SPL

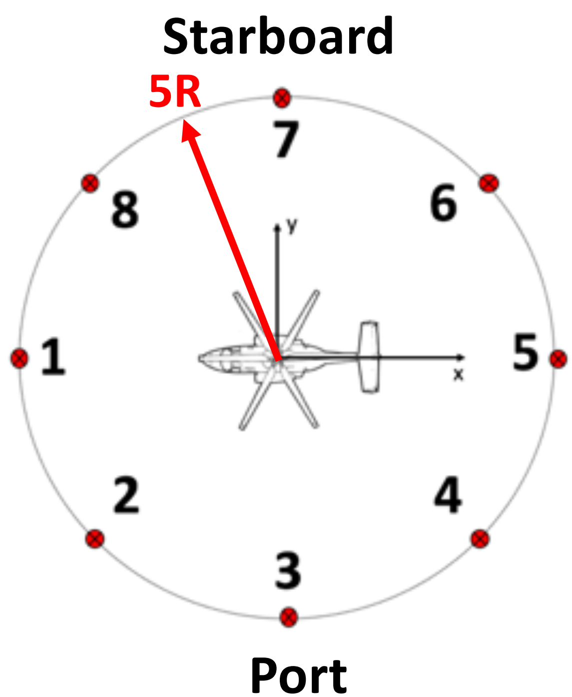




Results: Lift-Offset Coaxial Rotor

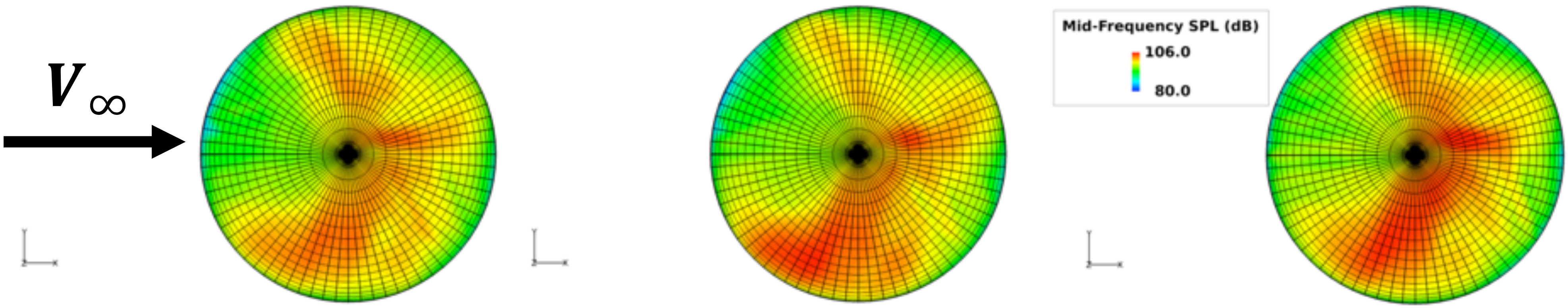
- Effect of rotor-to-rotor separation distance at 150 knots
- Comparison of mid-frequency SPL



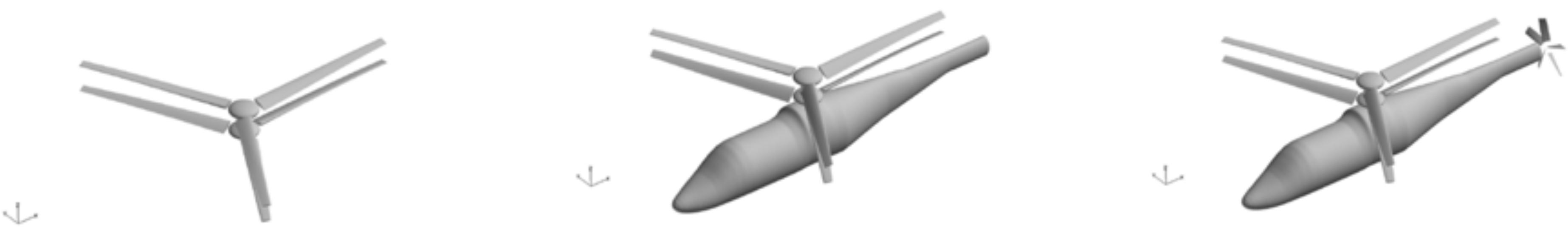


Results: Lift-Offset Coaxial Rotor

- Hemispherical observer-grid simulation (10R)
- Computed rotor noise only



Isolated Rotor Case	Fuselage Case	Full Config Case
Min: 79.3 dB	Min: 80.6 dB	Min: 79.7 dB
Max: 104.1 dB	Max: 105.6 dB	Max: 106.6 dB



Summary of Results: Lift-Offset Coaxial Rotor

- **BVI** and **blade-crossover events** are the most dominant aerodynamic interactions of a lift-offset coaxial rotor.
- The lift-offset coaxial rotor showed higher mid-frequency SPL at a **negative pitch attitude, higher speed, higher LO, and lower rotor separation distance**.
- Significant **improvement** in rotor acoustics and vehicle power performance at a **positive pitch attitude**.
- **Full-configuration** model showed **higher** noise than that of the isolated coaxial rotor model.

Part 2: Urban Air Mobility Aircraft

Introduction: UAM vehicles

- **Hybrid or fully-electric vertical take-off and landing (VTOL) aircraft become increasingly popular**
- **The concept of Urban Air Mobility (UAM)**
  - **Provide green, efficient, safe, and affordable urban air transportation**
  - **Alleviate traffic congestion**
  - **Interconnect urban and suburban areas**
- **UAM aircraft designs feature multi-rotors and fixed wings**

Ref: DaSilva, J. L., "Traffic Consistently Bad in Bay Area", The Pioneer, Oct. 2nd, 2017

Hyundai's Full-Scale Air Taxi Concept

Ref: https://evtol.news/2020/01/06/uber-and-hyundai-motor-announce-partnership/

Introduction: UAM vehicles

- Both aerodynamics and acoustics of multi-rotor configurations could be significant different from that of conventional helicopters
- Noise is a potential barrier to public acceptance
- Uber's guidelines:
  - 15 dB lower than similar-sized helicopter noise (Ref: Hayes and Stevenson, UAS Traffic Management News, 2019)
  - Less than 67 dB (A-weighted) from the ground level at 250 ft (76 m) (Ref: Holden and Goel, Uber Elevate, 2016)

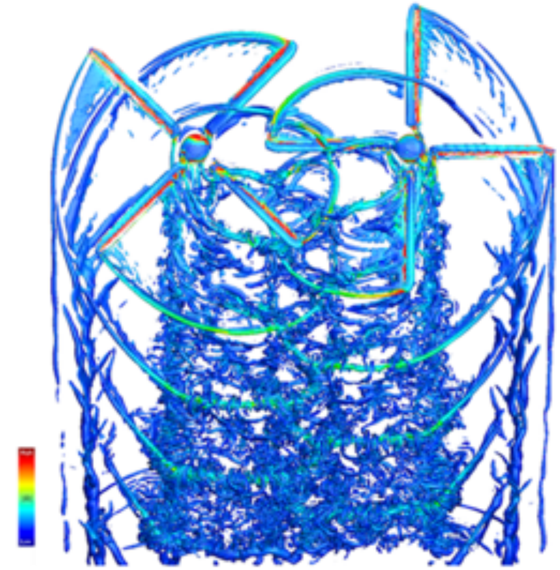
NASA's Quadrotor Configuration

NASA's Side-by-Side Rotor Configuration

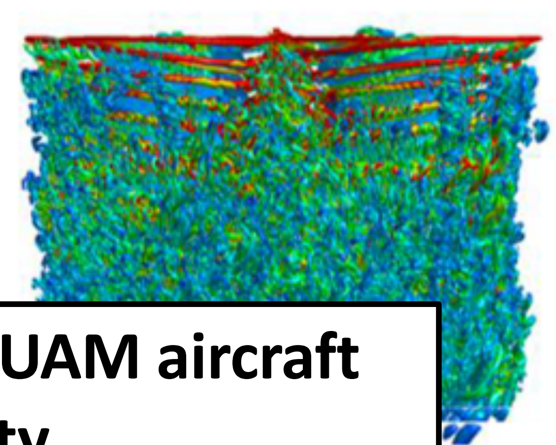
Courtesy of Dr. Johnson and Chris Silva from Rotorcraft Aeromechanics, NASA Ames

Introduction

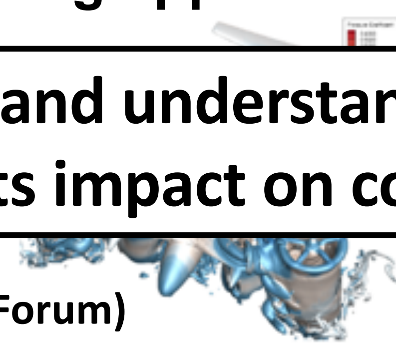
- Ventura Diaz et al. (2019 VFS Forum) showed rotor-to-rotor BVI could be a potential noise source of a side-by-side rotor
- Sagaga and Lee (2020 AIAA Aviation Forum) demonstrated that hover performance of a side-by-side rotor could be reduced with increasing rotor overlap
- Li and Lee (2020 VFS SJ Forum) calculated broadband noise of a quadrotor UAM vehicle design based on UCD QuietFly and demonstrated its importance at high frequency
- Thai et al. (2020 VFS SJ Forum) demonstrated a multi-rotor trim loose coupling approach for UAM aircraft simulations



Ref: Ventura Diaz et al. (2019 VFS Forum)



Very limited research and understanding of UAM aircraft noise and its impact on community.



Ref: Thai (2020 VFS SJ Forum)

Ref: Sagaga and Lee (2020 AIAA Aviation Forum)

Introduction: Research Objectives

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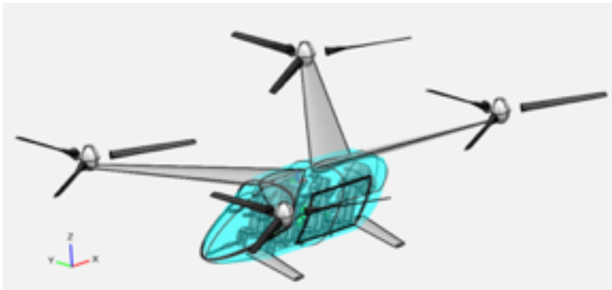
- Simulate UAM aircraft acoustics based on a high-fidelity CFD approach with prescribed rotor motions.
- Identify potential acoustic sources of the selected multi-rotor UAM aircraft models.
- Perform parametric studies (e.g., rotor-to-rotor overlap).
- Compare the UAM aircraft noise with conventional helicopter noise and various background noise levels (e.g., freeway noise).

Methods: Aircraft Models

- NASA's 1-passenger quadrotor
- NASA's 6-passenger quadrotor
- NASA's 6-passenger side-by-side rotor (0%, 5%, 15%, and 25% overlap)



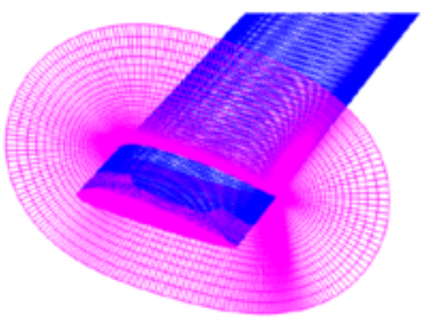
Properties	1-Passenger Quadrotor	6-Passenger Quadrotor	6-Passenger Side-by-Side Rotor
Number of Rotors	4	4	2
Rotor Radius (ft)	6.5	13.1	10.5
Nominal RPM	662	400	499
Payload (lb)	220	1,200	1,200

Methods: CFD Mesh

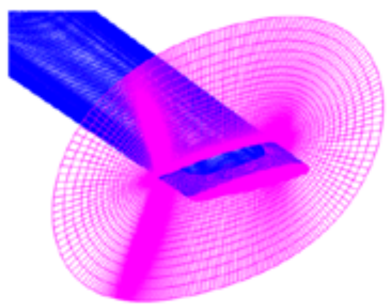
- **Near-body:**
  - **Overset structured mesh generated using Chimera Grid Tools**

	Chordwise	Spanwise	Normal	Total/Blade
Side-by-Side	265	168	65	3.0 M
1-Pass Quad	239	171	65	3.6 M
6-Pass Quad	239	171	65	3.6 M

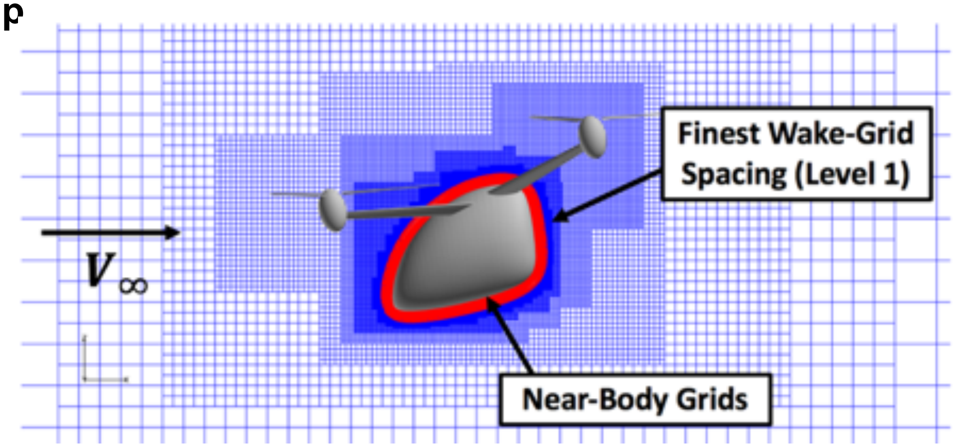
- **Off-body:**
  - **8 levels adaptive mesh refinement (AMR) with the finest wake-grid spacing equal to 10% C_{tip}**



Blade Root



Blade Tip



Methods: CFD Setup

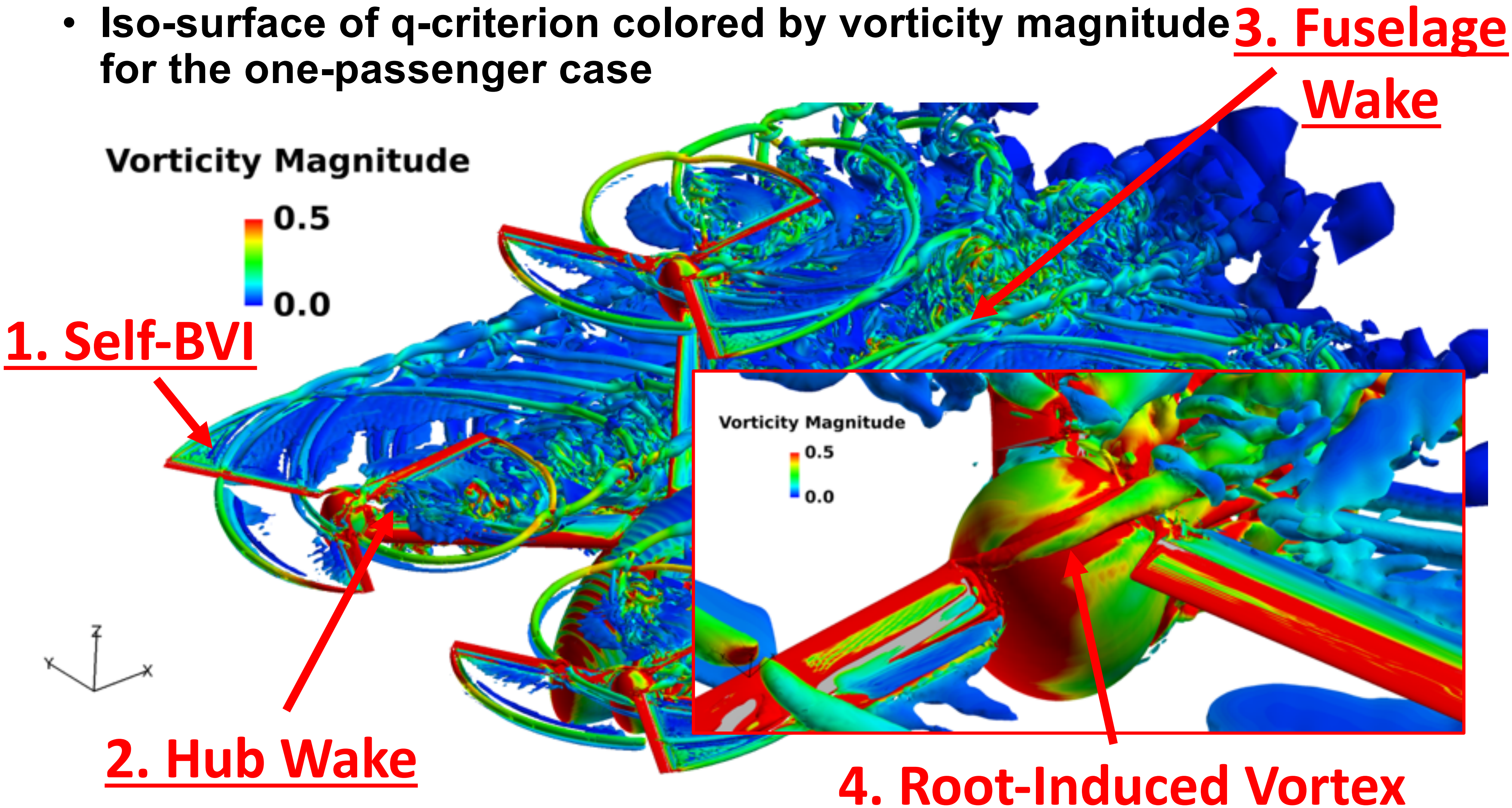
- **Summary (Helios simulations):**

Input Parameters	Near-Body Grid	Off-Body Grid
CFD solver	OVERFLOW	SAMCART
Spatial scheme	5th order	5th order
Temporal scheme	2nd order	2nd order
Time step size	0.25^{o}	
Turbulence Model	SA-DES	
Frequency of blade surface output	0.50^{o} (every two time steps)	

- **UAM vehicle trim: prescribed motion**
- **Simulations converged after 5 rotor revolutions**

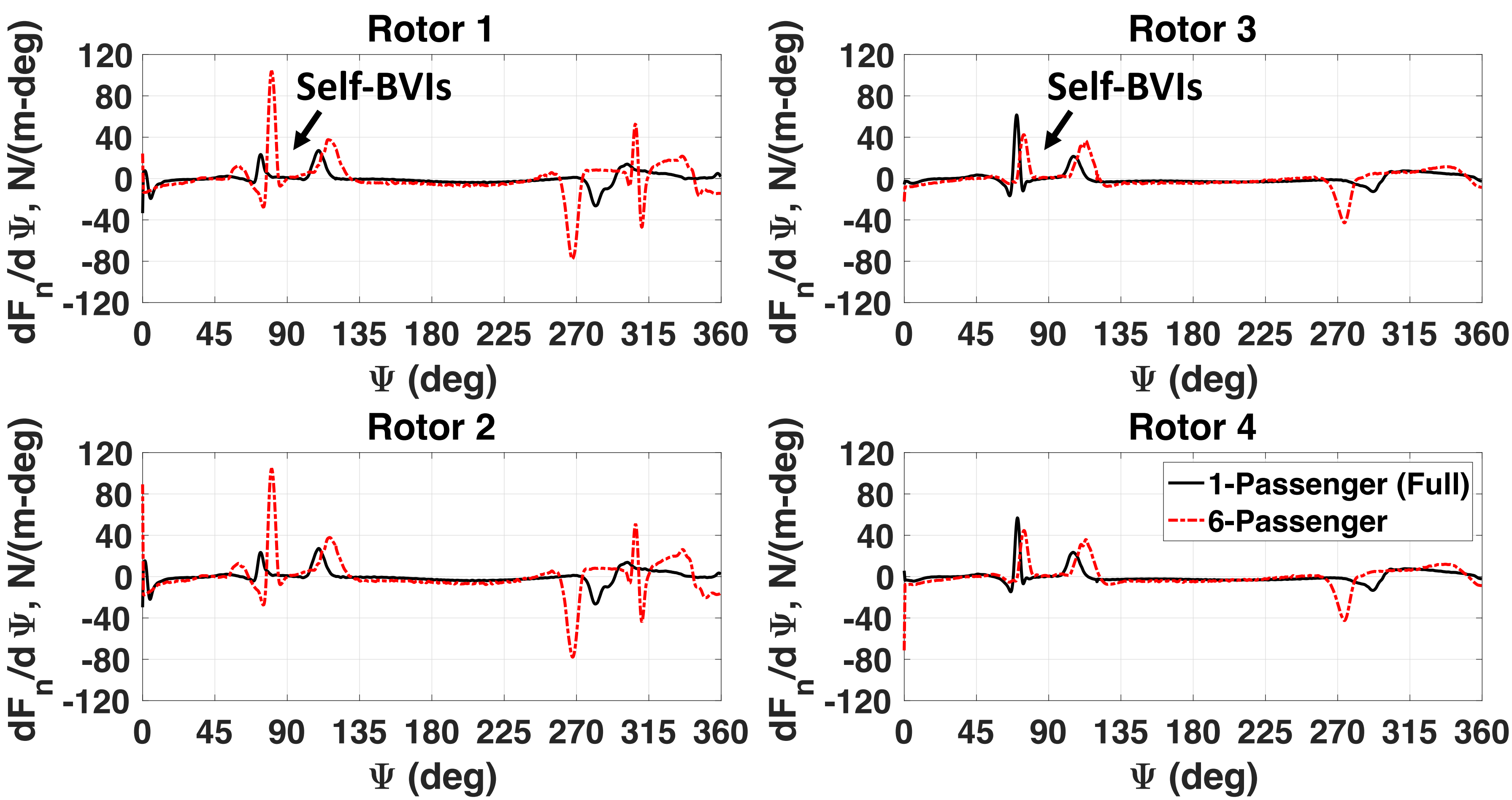
Results: Quadrotors

- Performed forward flight simulations at 70 knots and an altitude of 5,000 ft
- Iso-surface of q-criterion colored by vorticity magnitude for the one-passenger case



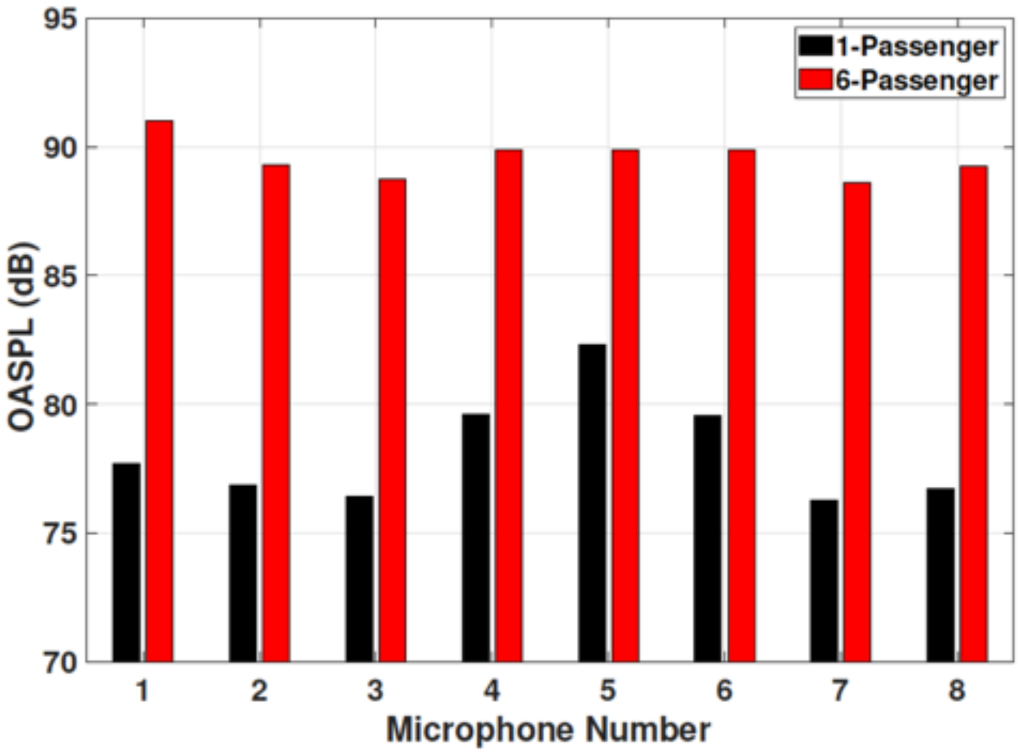
Results: Quadrotors

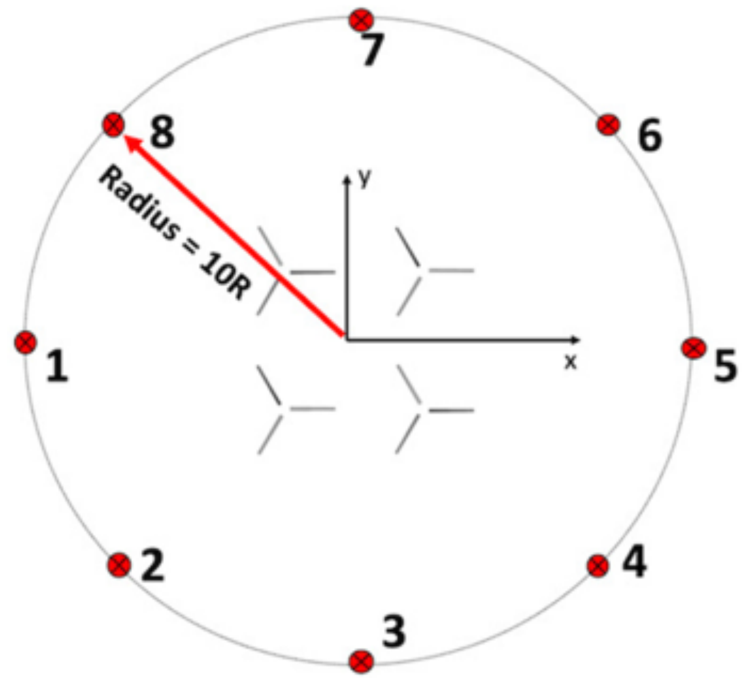
- **Comparison azimuthal derivative of sectional normal force at 75% span**



Results: Quadrotors

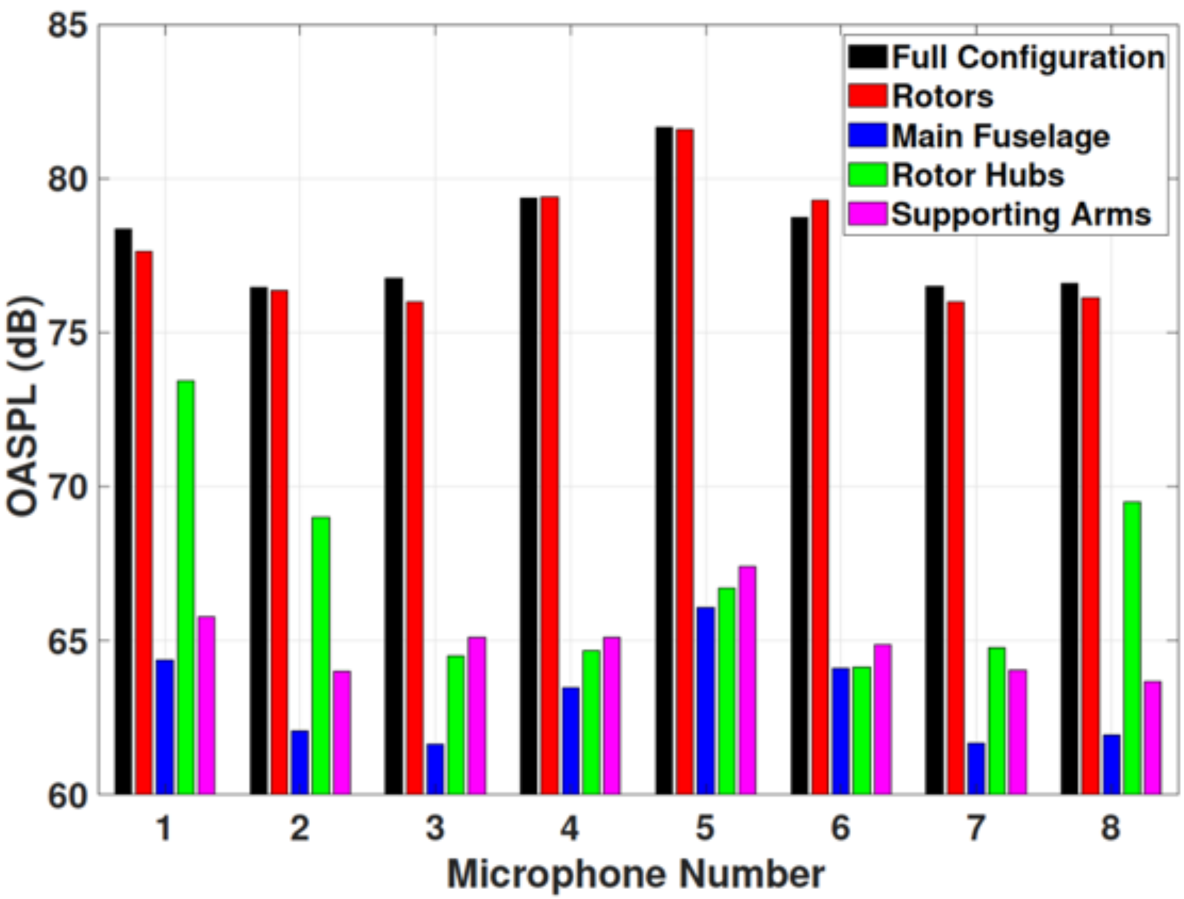
- **Comparison of overall sound pressure level (OASPL)**

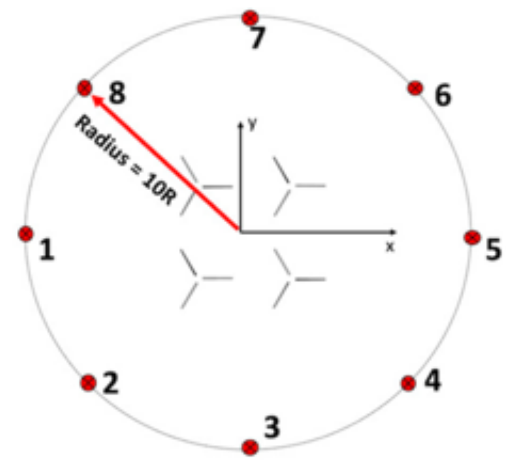




Results: Quadrotors

- **Decomposition of the vehicle noise for the one-passenger full configuration case.**





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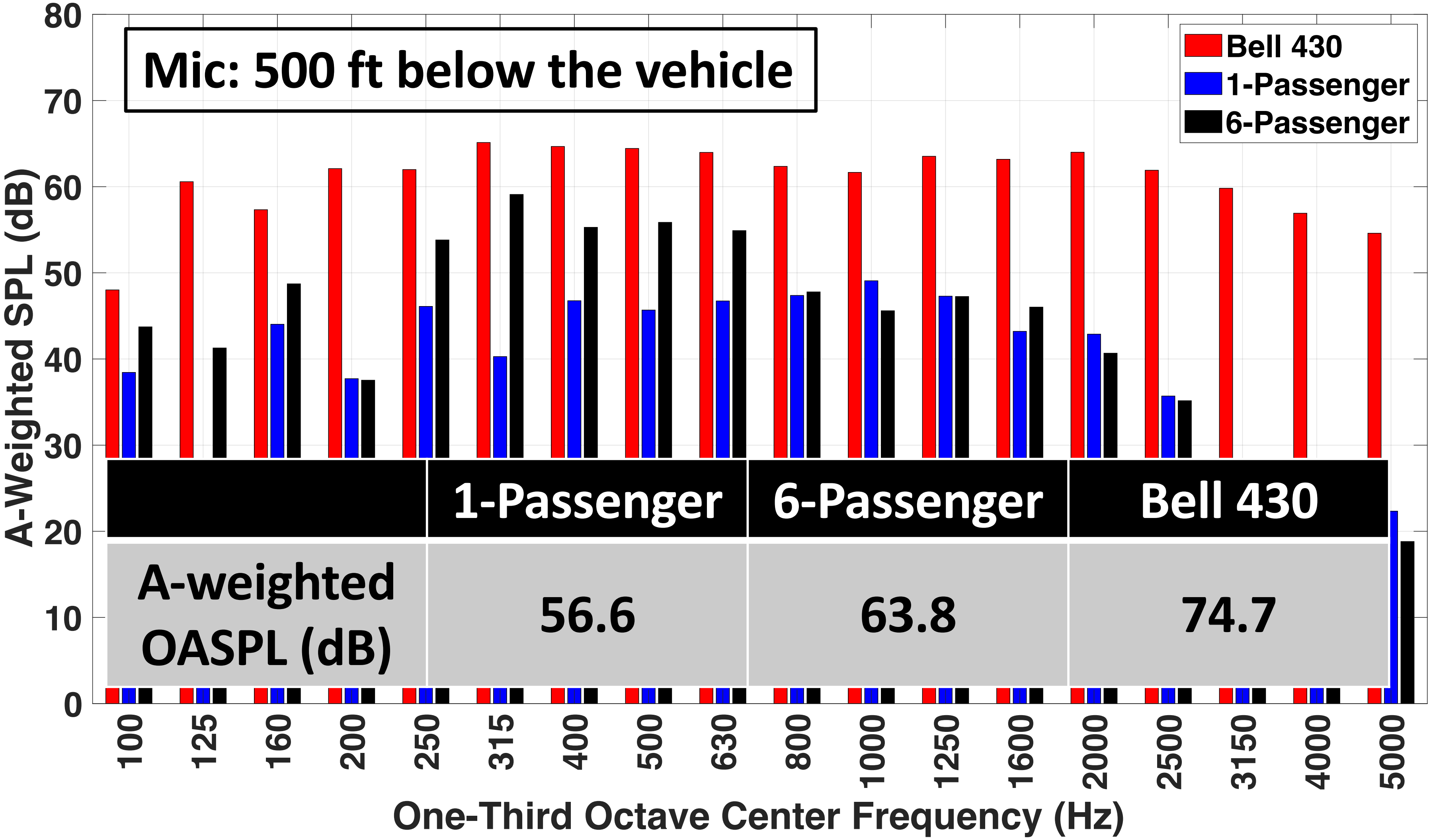
Results: Quadrotors

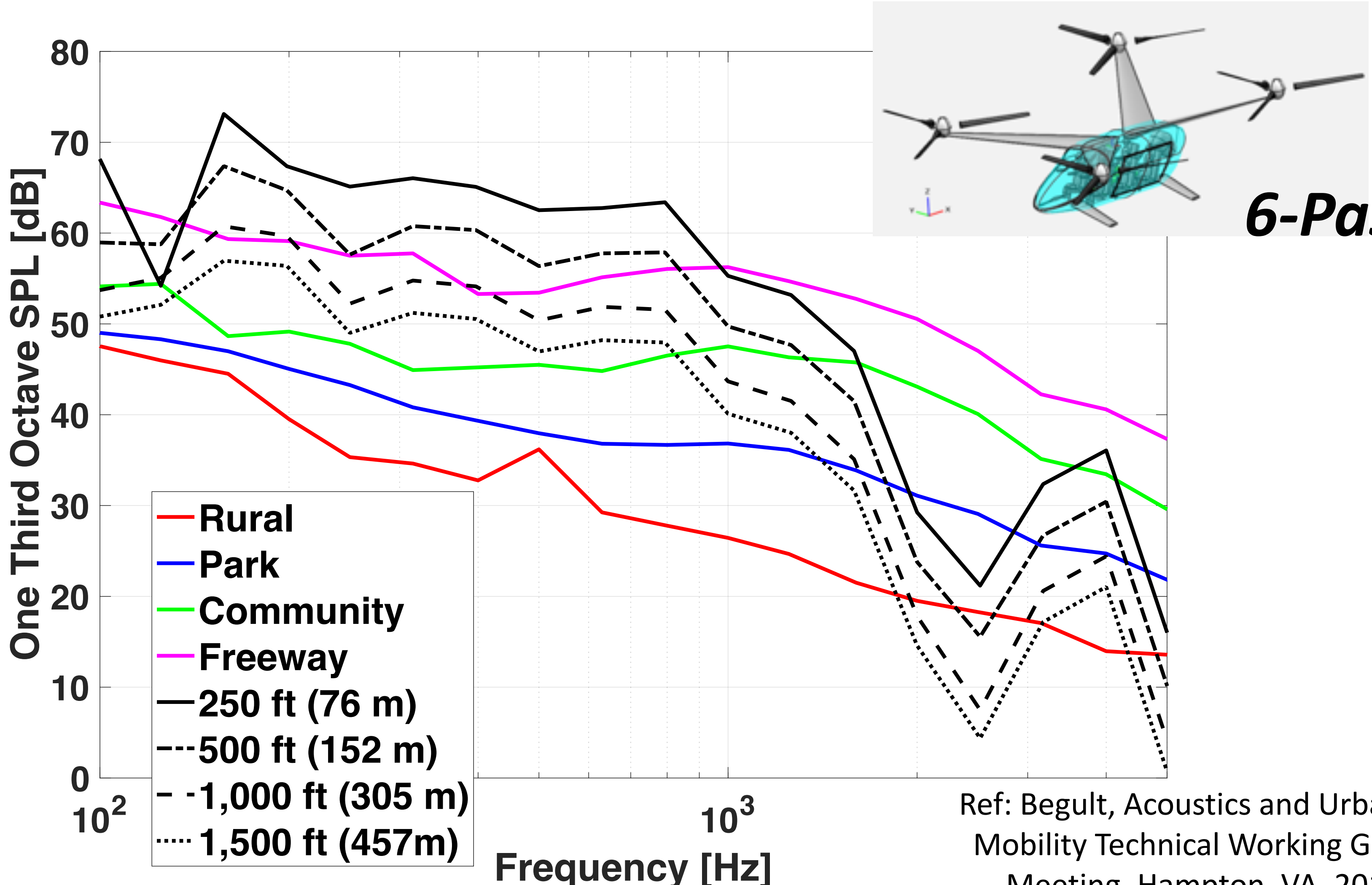
- **Comparison against similar-sized conventional helicopter noise**



	1-Passenger	6-Passenger	Bell 430
A-weighted OASPL (dB)	56.6	63.8	74.7

Results: Quadrotors

- **Comparison against the background noise data measured by Begault (NASA Ames) in the Bay Area, CA**



6-Pass

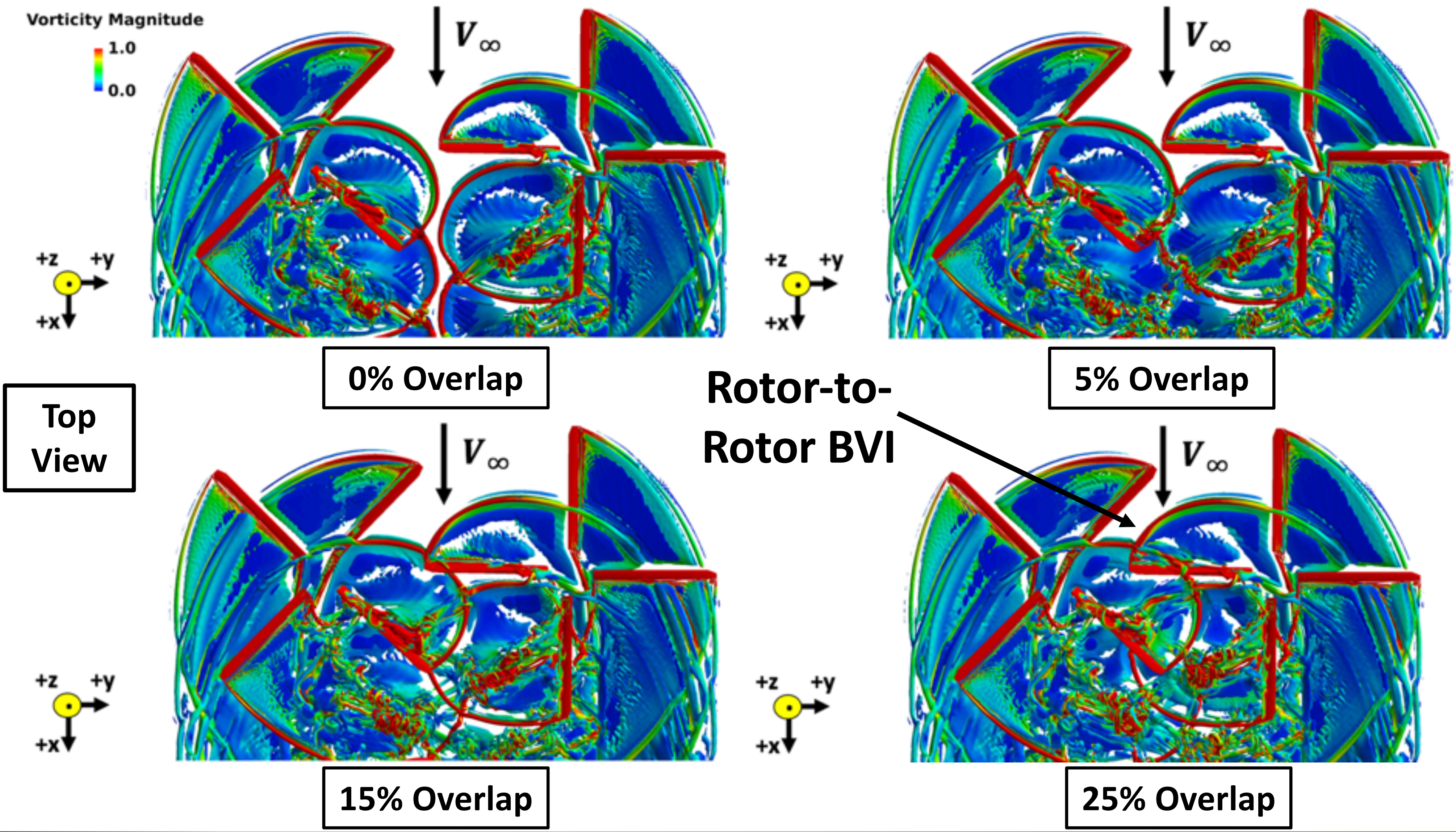
Ref: Begult, Acoustics and Urban Air Mobility Technical Working Group Meeting, Hampton, VA, 2019

Summary of Results: Quadrotors

- **BVI** is the **most dominant noise source** of the selected quadrotor UAM aircraft.
- The six-passenger quadrotor with **higher payload** shows **higher overall sound pressure level** than the one-passenger quadrotor
- The six-passenger quadrotor is only **10 dB quieter** than the conventional helicopter Bell 430. A goal of **15 dB quieter** than similar-sized conventional helicopter noise is still **challenging**.
- The six-passenger quadrotor noise **could not be completely masked** by the **highway noise** level even at altitude of **1,000 ft**. Noise in low-altitude operations could be a potential concern.

Results: Side-by-Side Rotor

- Simulations performed at 115 knots and an altitude of 5,000 ft
- A total of four overlap cases are considered: 0%, 5%, 15%, and 25%

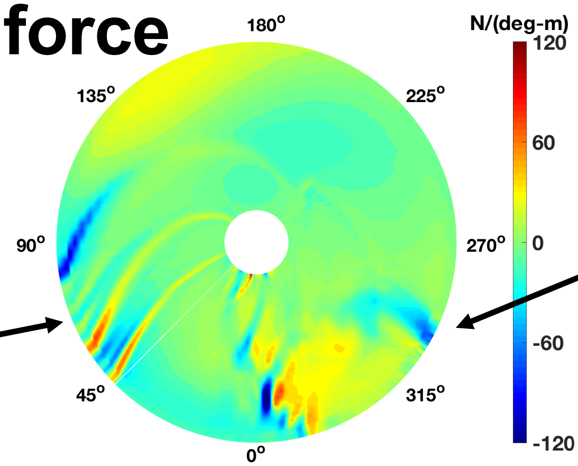


Results: Side-by-Side Rotor

- Comparison of the azimuthal derivative of sectional normal force

Left Rotor (CW)

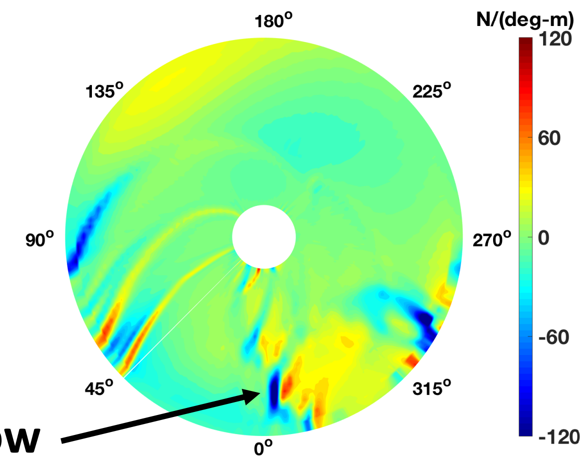
Self BVIs



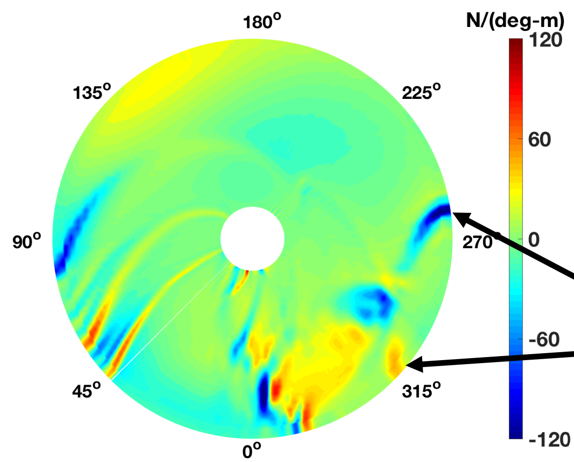
0% Overlap

Self BVIs

Separated Flow Interaction



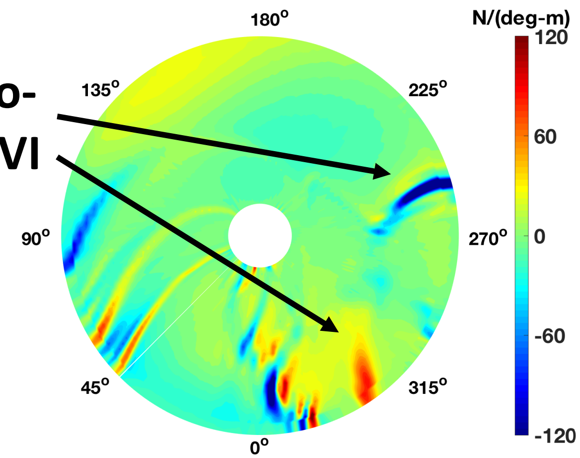
5% Overlap



Rotor-to-Rotor BVI

15% Overlap

Rotor-to-Rotor BVI

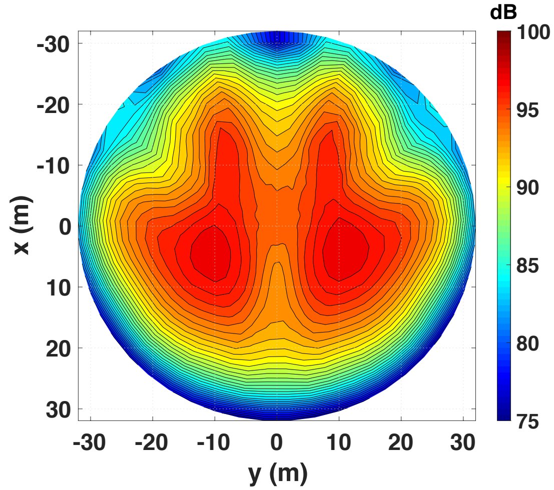


25% Overlap

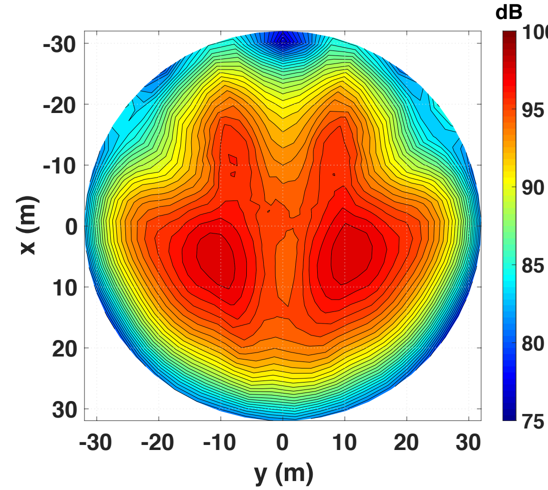
Results: Side-by-Side Rotor

- **Acoustics simulation performed on a hemispherical grid with a radius = 10R**

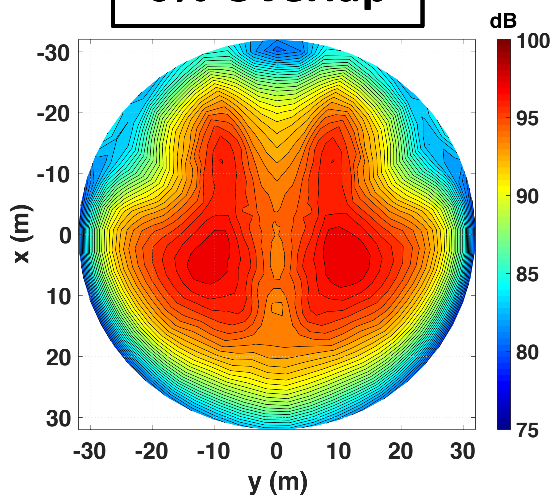
Comparison of OASPL from the Top View



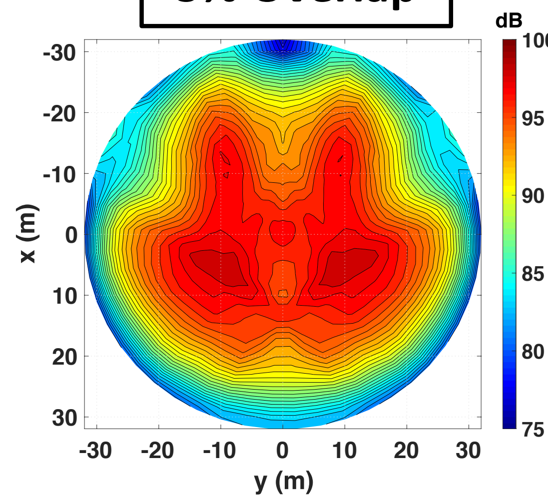
0% Overlap



5% Overlap



15% Overlap



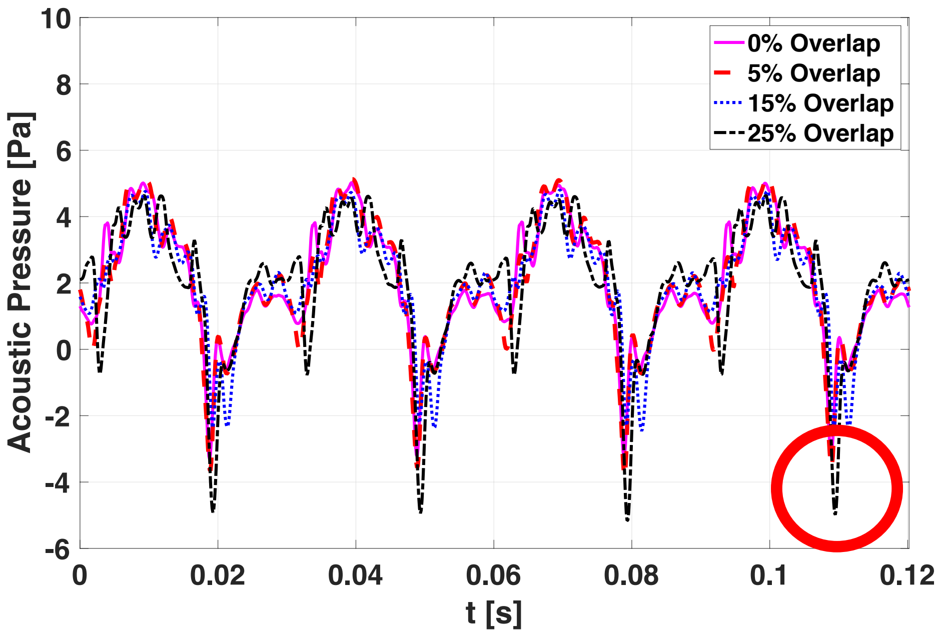
25% Overlap

Results: Side-by-Side Rotor

- **Noise source identification**

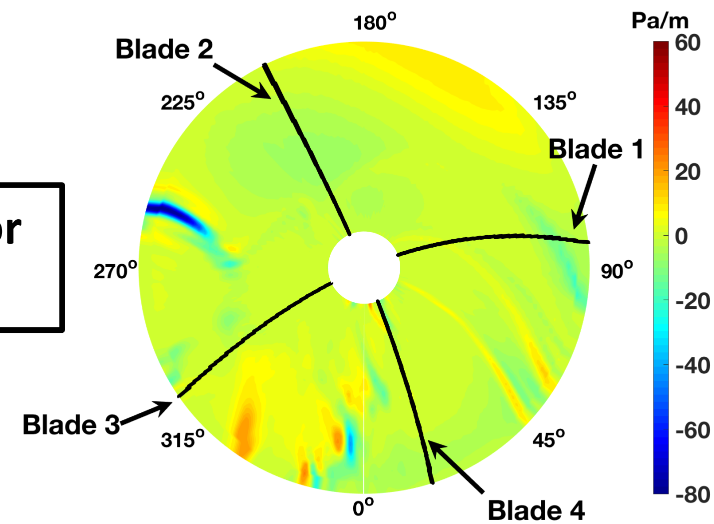
$$\frac{1}{c}\int_{f=0} \boxed{\left[\frac{\dot{l}_r}{r|1-M_r|^2}\right]_{ret}} dS$$

Loading noise at the max OASPL location



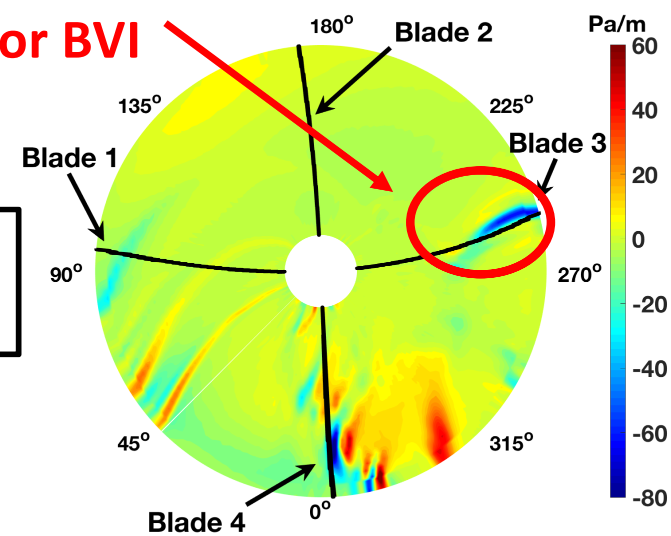
V_∞

Right Rotor (CCW)



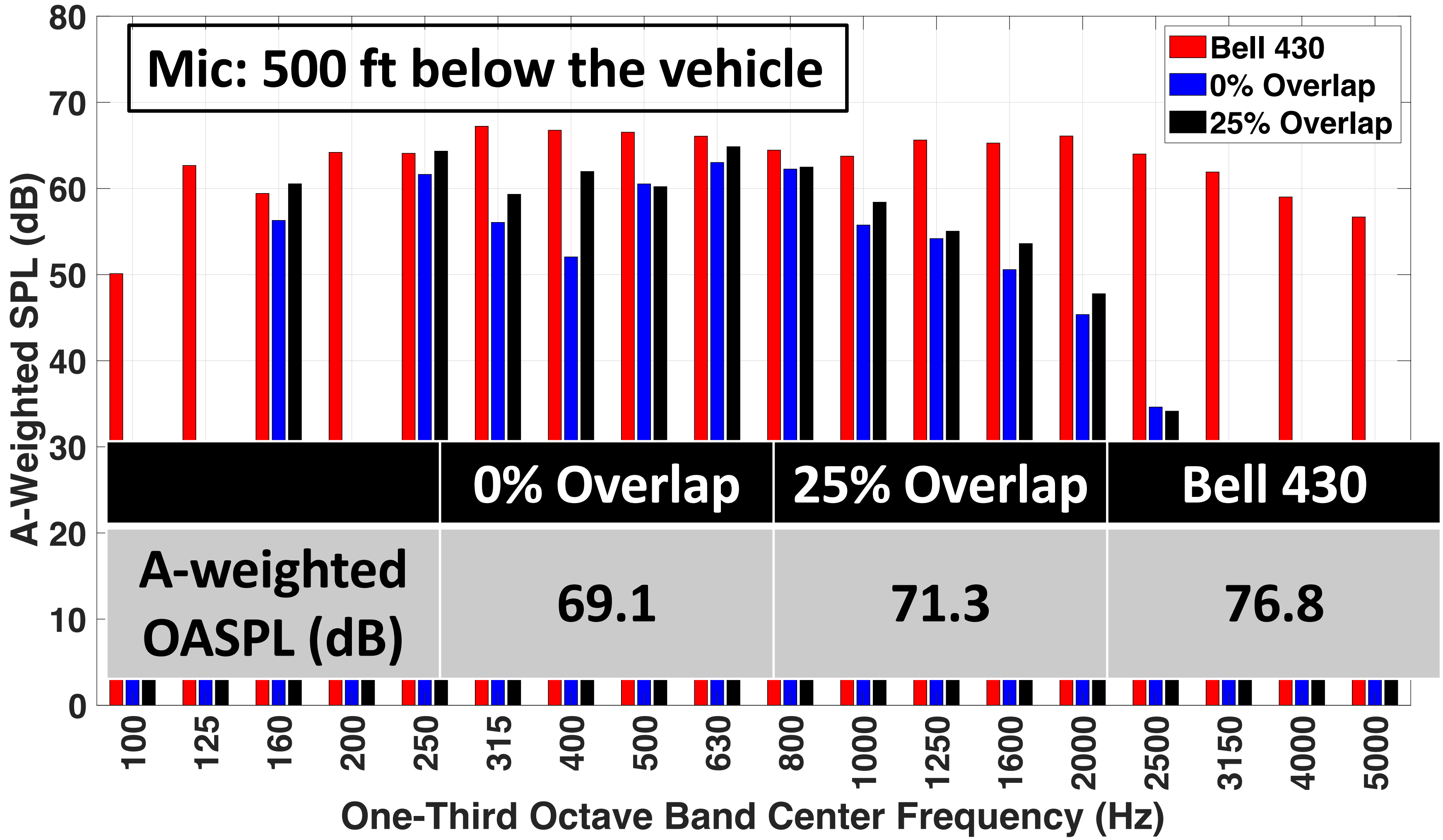
Rotor-to-rotor BVI

Left Rotor (CW)



Results: Side-by-Side Rotor

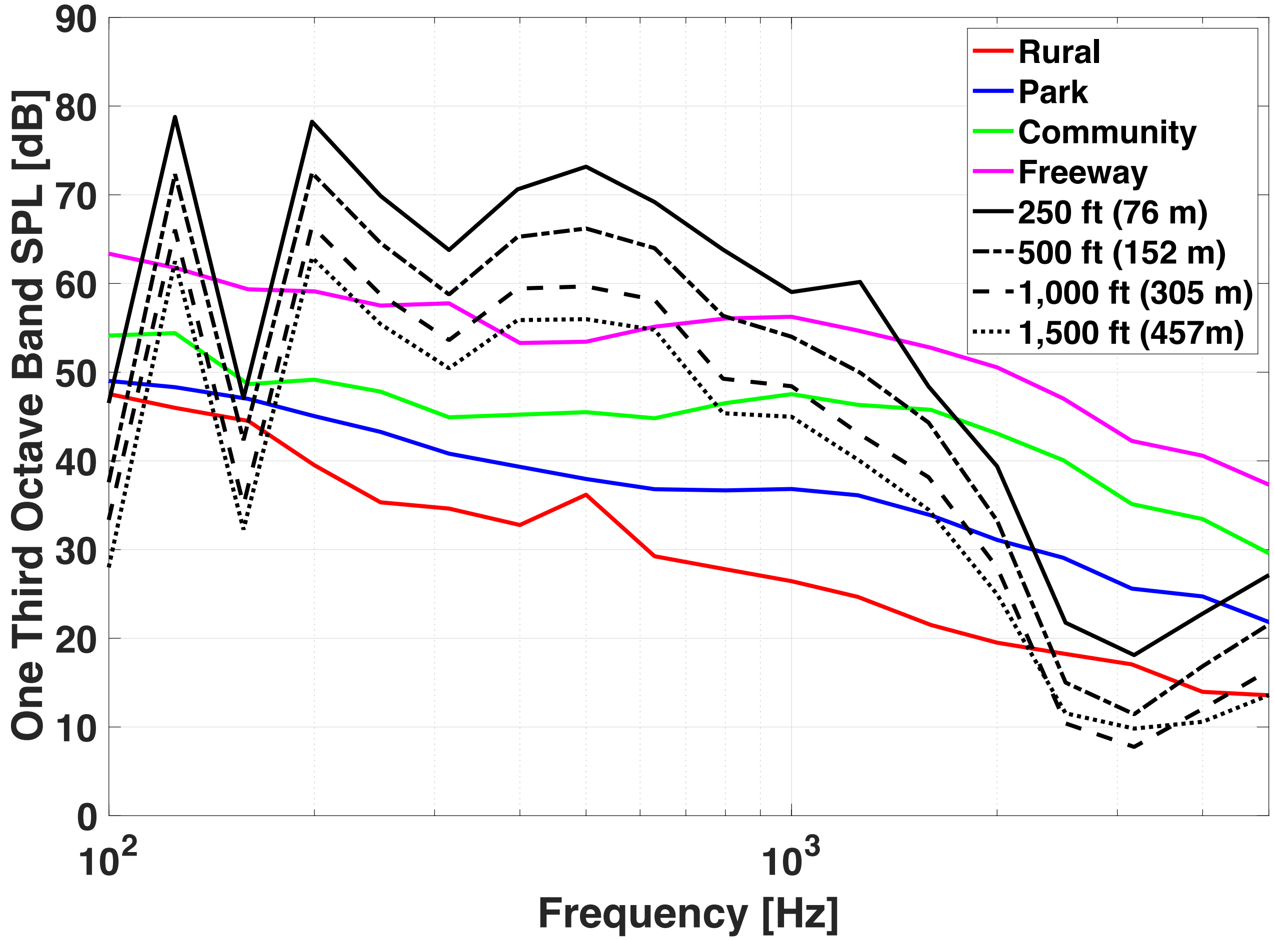
- **Comparison against similar-sized conventional helicopter noise**



	0% Overlap	25% Overlap	Bell 430
A-weighted OASPL (dB)	69.1	71.3	76.8

Results: Side-by-Side Rotor

- **Comparison against the background noise data measured by Begault (NASA Ames) in the Bay Area, CA**
- **0% overlap case:**



Summary of Results: Side-by-Side Rotor

- BVI events, particularly the rotor-to-rotor BVI events, are the most dominant noise sources.
- Rotor noise increases with increasing rotor overlap.
- The side-by-side rotor with 25% overlap is only 5 dB quieter than the conventional helicopter. The noise guideline of 15 dB quieter than similar-sized helicopter noise could not be met.
- The side-by-side rotor noise with 0% overlap has partially exceeded the freeway noise level even at an altitude of 1,500 ft. Noise reduction technology should be pursued.

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- Kalki Sharma and Ken Brentner at Penn State for internal discussions and useful inputs
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- Neal Chanderjian and Ahmad Jasim for their advice on CFD modeling
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Thank You
Questions?